DEVELOPMENT AND EVALUATION OF A NEW ZEALAND DIGIT TRIPLET TEST FOR AUDITORY SCREENING

A thesis submitted in partial fulfilment of the requirements

for the Degree of Master of Audiology

in the University of Canterbury

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University of Canterbury

2010

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AB Word List	Arthur Boothroyd word list
ASHA	American Speech-Language-Hearing Association
ANSI	American National Standards Institute
BM	Basilar Membrane
CID W-22	Central Institute for the Deaf W-22
dB HL	Decibels Hearing Level
dB SPL	Decibels Sound Pressure Level
DTT	Digit Triplet Test
HHIE-S	Hearing Handicap for the Elderly – screening version
HINT	Hearing-in-Noise Sentence Test
Hz	Hertz (number of cycles per second, unit of measure)
kHz	kilohertz (one thousand hertz)
IHCs	Inner Hair Cells
NU- No.6	Northwestern University Auditory Test No. 6
NZ	New Zealand
OHCs	Outer Hair Cells
PB - 50	Egan's phonetically balanced 50 word list
PTA	Pure Tone Audiometry
SNR	Signal-to-noise Ratio
SRT	Speech Reception Threshold
TM	Tympanic Membrane
WHO	World Health Organisation

ACKNOWLEDGEMENTS

Special thanks to my supervisor, Dr. Gregory O'Beirne, for the design of the Digit Triplet Test software and for his encouragement, support and guidance for the direction of this work. I also wish to thank my second supervisor, Natalie Rickard, for her input to my writing style and for her support. In addition, thank you to GN Resound for the financial support provided for this thesis.

I also wish to thank my participants, many of whom endured more than one testing session required for this study. I especially want to thank the University of Canterbury Library staff, former colleagues, for their encouragement, participation and general support of me while I completed my Master of Audiology.

Thank you to my parents, Alan and Beverley King, and my son Joshua, for their belief and support for me returning to University to pursue a new career. Also special thanks to my many friends and audiology classmates who supported me over the last two years while I completed my studies. Thank you to my friends, Fiona Yip, Kinau Venter and Geraldine Spencer, for their support during the writing of this thesis.

ABSTRACT

The aim of this study was to develop a Digit Triplet Test (DTT) using NZ English. The DTT is a hearing screening tool that uses spoken numbers presented in background noise to estimate speech recognition thresholds (SRT_n). The NZ DTT will be made available via telephone or the internet, and will provide each person who completes the screening test with information about whether they should seek a professional hearing assessment.

Normal-hearing participants (22 listeners) with hearing thresholds ≤20 dB HL were tested to establish the intelligibility of the individual digits at various signal-to-noise ratios (-20; -17.5; -15.0; -12.5; -10.0; -7.5; and -5.0 dB). The mid-points of the resulting psychometric functions were then used to adjust the level of each digit to achieve the same intelligibility. A SRT of -10.40 ± 1.75 dB SNR for the broadband presentation was established for the separate ear triplet test with the average slope of 17.3%/dB ± 3.9 %/dB for the ten test lists generated. The binaural ear DTT results were compared to best ear threshold PTA and found to have a highly significant correlation ($r = 0.816$, $p<0.001$) and a significant correlation to the QuickSIN sentence-in-noise test ($r = 0.668$, $p<0.001$). The binaural triplet test was found to have a sensitivity of 100% and specificity of 85%.

The separate ear DTT results were compared to the best ear threshold pure tone audiometry and found to have a highly significant correlation ($r = 0.809$, $p<0.001$). The separate ear triplet test was found to have a sensitivity of 88% and specificity of 81% (1 – specificity = 0.187). The internet version of the DTT hearing screening test will provide New Zealanders with an easily accessible and objective test that will raise awareness about hearing and hopefully reduce the length of time people take before seeking advice about their hearing.

1 INTRODUCTION

1.1 Consequences of Hearing Impairment on Communication

Communication is an important part of our societal and personal relationships. Hearing loss strikes at the very core of our social interactions. The potential for negative social consequences increases as older adults live longer with impaired hearing. Age-related hearing impairment, or presbycusis, is a sensory deficit that many normal ageing persons will experience (Dalton et al., 2003; Nachtegaal et al., 2009; Weinstein & Ventry, 1982). The emotional effects of strained communication experienced by the individual with the hearing loss and by their significant other and family members is only starting to be examined by social sciences (Hallberg, 1999). What is beginning to be understood is that the stigma and avoidance of admitting to a disability affects more than just the person with the hearing loss (Brooks & Hallam, 1998; Hallberg, 1999; Helvik, Jacobsen, & Hallberg, 2006a; Nachtegaal et al., 2009; Tesch-Römer, 1997; Weinstein & Ventry, 1982). A change in social attitudes to hearing loss is vital so that intervention to restore hearing ability as much as possible is accepted as the normal course of action. When people are more accepting of using listening devices, the result will be an improvement in the quality of life for the person with the hearing loss and the people with whom they interact, particularly significant others in their life (Hallberg, 1999; Tesch-Römer, 1997).

Unless an adult loses their hearing suddenly due to an illness or head trauma, the change is generally so gradual they are often not aware of the loss. People tend to adapt their social activities to fit their hearing (Helvik et al., 2006a). As people age, they also tend to underestimate their hearing loss (Nondahl et al., 1998; Wiley, Cruickshanks, Nondahl, & Tweed, 2000). Hearing impairment can lead to coping strategies that socially isolate people, resulting in psychological stress and maladaptive behaviours that negatively impact on family and society. People may employ negative self-centred behaviours such as reducing social interactions. They often give spouses, family and friends invalid reasons for the changes in their behaviour and deny hearing loss as the cause for these behavioural changes (Hallberg, 1999; Helvik, Jacobsen, & Hallberg, 2006b; Koopman, Davey, Thomas, Wittkop, & Verschuure, 2008; Nachtegaal et al., 2009). Hallberg (1999) reported on several studies that found negative social consequences associated with hearing impairment including loss of status, loss of independence, dysfunction in families and the breakdown of communication between partners. Often other family members are aware of the hearing loss before the affected person even admits to the hearing impairment, because the impairment is making meaningful communication so difficult (Dalton et al., 2003; Hétu, Jones, & Getty, 1993; Weinstein & Ventry, 1982).

The World Health Organisation (WHO) lists hearing loss as a disability in the International Classification of Functioning, Disability and Health (ICF). Hearing loss is described in terms of ‘activity limitation’ and ‘participation restriction’. Helvik et al., (2006) found that increased hearing impairment was related to a decrease in active participation in activities resulting in a form of ‘activity limitation’ that fits within the ICF framework. Recognition by the ICF that auditory limitations do in fact affect people in complex ways ensures that more research is channelled into examining the consequences of hearing loss on people and society (Helvik et al., 2006a; Hétu et al., 1993).

The ability to hear also fulfils a number of other important communication functions that are related to personal safety and health; for example, the ability to detect events without seeing them, such as hearing the telephone or door bell ring and the warning signals of smoke alarms or sirens (Wallhagen, 2010). A hearing person is able to localise sound and orient themselves in their environment. This ability can provide important safety information and a person with a hearing loss may not receive this essential information (Wallhagen, 2010). The ability to hear also supports positive psychological health, as hearing provides people with opportunities to enjoy music, participate in group activities, and enjoy talking books, for example, all of which have the potential to increase emotional wellbeing. Hearing loss negatively impacts on emotional wellbeing, and with more elderly people living on their own in our society there is an increased risk for social isolation and depression (Dalton et al., 2003; Nachtegaal et al., 2009; Tesch-Römer, 1997; Wallhagen, 2010; Weinstein & Ventry, 1982).

Ideally, an interdisciplinary approach would be taken by health professionals, government and educational bodies towards changing social attitudes and beliefs about hearing impairment. If society were more accepting of the impact of hearing loss on an individual and on that individual’s communication partners, attitudes towards the wearing of hearing aids may change. The first step towards improving society’s acceptance of hearing aids, so that hearing aids are accepted in much the same way as prescription glasses are accepted as the appropriate solution for visual deterioration, is to raise awareness of the problem.

2 Understanding How We Hear

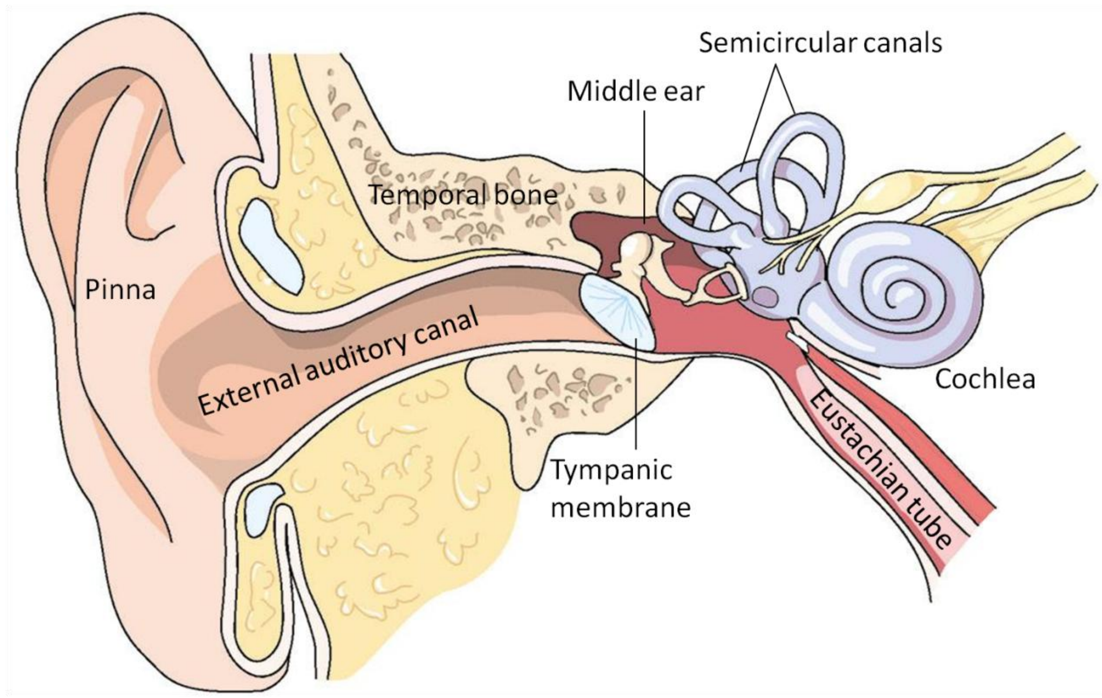

Figure 1. Illustration of the outer ear, middle ear and inner ear adapted from course material provided by Dr. N. Rickard, University of Canterbury.

The human ear can be divided into three functional sections: the outer, middle and inner ear. As illustrated in Figure 1, the outer ear is made up of a pinna that directs sound waves into the ear canal. The shape of the pinna directs acoustic stimuli into the ear canal in such a way as to provide clues for sound localisation. The pinna also can produce a gain in sound pressure at some frequencies of 10 -15 dB which improves the transmission of the sound to the middle ear system (Pickles, 2008).

The middle ear system acts as a transformer by taking sound pressure energy and translating it into mechanical energy. The system includes the tympanic membrane (ear drum) and the ossicular chain, which is made up of three small bones called the malleus, the incus and the stapes. These bones transform and match the low impedance of airborne sound to the high impedance of the fluid-filled inner ear. The bones rotate and transfer the force to the stapes which is attached to the flexible oval window in the wall of the inner ear (Pickles, 2008).

The inner ear consists of the vestibular system which is responsible for balance, and the cochlea which is responsible for hearing. The cochlea is divided along its length by two membranes. Reissner's membrane separates the scala vestibuli from the scala media. The scala media houses the organ of Corti that contains the OHCs and IHCs which are responsible for transforming pressure changes into electrical potentials. The organ of Corti is situated between the basilar membrane (BM) and the tectorial membrane (TM). Below the TM is the scala tympani. At the base of the cochlea is the oval window and at the apical end of the cochlea is a small opening known as the helicotrema. Another opening, the round window, is situated at the base of the cochlea in the scala tympani. The inward movement of the oval window is first generated by the staples footplate in the middle ear which starts a chain reaction of fluid movement, often referred to as the transverse travelling wave (Patuzzi, 2009). The fluid pressure exerted through the fluid-filled chambers results in the outward movement of the round window. The helicotrema connects the two outer chambers of the cochlea (scala vestibuli and scala tympani) and eliminates any pressure differences that occur between the two chambers (Moore, 2007). On the outer wall of the cochlea is the structure called stria vacularis which provides the nutrients and the voltage (electrical potentials) essential for the normal function of the cochlea.

The organ of Corti contains two types of hair cells. The OHCs are arranged in three rows on the outside of the tunnel of Corti which sits between the BM and the TM. The IHCs form one row of cells on the inside of the tunnel of Corti. Both hair cells have tufts of hair-like structures, called stereocilia, at their apexes (Moore, 2007; Musiek & Baran, 2007). There are approximately 12,000 OHCs and 3,500 IHCs (Moore, 2007; Musiek & Baran, 2007; Pickles, 2008). The OHC stereocilia appear to be embedded into the tectorial membrane which hinges at its medial end. The up and down movement of the BM creates a shearing motion in the TM which moves the OHCs' stereocilia sideways. The OHC movement is transferred to the fluid filling the upper part of the organ of Corti which flows to move the IHC stereocilia. The movement of the IHC stereocilia generates a flow of electrical current through the IHCs, facilitated by the opening of ion channels in the tips of the stereocilia (Musiek & Baran, 2007) which in turn results in the release of neurotransmitters and the generation of action potentials (nerve firing) in the auditory nerve. The activity of the auditory nerve is relayed through the central auditory pathways to the auditory cortex and interpreted as sound.

The strength of the initial signal is dependent on the response of the OHCs to the BM movement. OHCs have a motor function whereby they change their length and shape in response to the BM movement. The OHC mobility, referred to as the cochlear amplifier, increases the fluid movement (signal) to the IHCs. This in turn influences the amount of the neural activity generated by the IHCs (Moore, 2007; Pickles, 2008).

The hair cells are sensitive to damage from a variety of causes such as exposure to loud noise or ototoxins, and the basal region of the cochlea is particularly sensitive. The basal region is maximally sensitive to high frequency sound stimuli, whereas the apical end of the BM is maximally responsive to low frequency stimuli. Damage in the basal region of the cochlear, therefore, does not typically affect low frequency hearing acuity, but results in a high frequency hearing loss (Patuzzi, 2009).

2.1 Physiological Relationship to Auditory Performance

The physiological condition of a person's auditory system is correlated to their performance on psychophysical auditory tests. While it is not a perfect relationship, the behavioural thresholds that are measured by audiological testing are related to the activity of the auditory system (Pickles, 2008). As described above, the transverse travelling wave has a characteristic place of resonance along the BM for each sound stimulus and this wave is enhanced by the OHC active process. Disruptions to OHC function due to damage will subsequently affect IHC activity. The resulting impairments can be assessed by measuring 'tuning curves' which plot mechanical, neural, or psychophysical responses to stimuli (Pickles, 2008). Each nerve fibre has a characteristic frequency to which it is most sensitive, and the tuning curve is a measure of the threshold for that nerve. The characteristic frequency of each nerve attached to the hair cells is ordered along the BM in a tonotopic arrangement which is repeated in the auditory nerve and in higher order nuclei structures (Moore, 2007). Research has shown that damage to the cochlea disrupts the OHC active mechanism such that the response of the tuning curve is less sharply tuned. As a result, sounds need to be more intense to produce the same magnitude of response (Figure 2) (Moore, 2007).

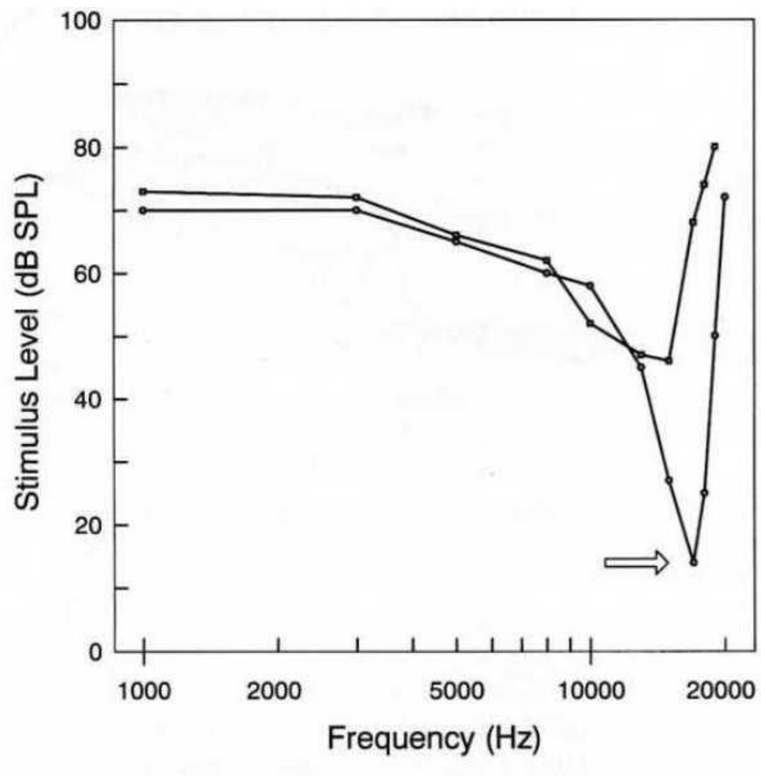

Figure 2. Idealized tuning curves based on findings by Sellick et al (1982) as cited by Gelfand (2001). The sharply peaked curve represents a healthy cochlear neural response (arrow). The broad curve represents OHC damage with intact IHCs. The sharply tuned tip of the tuning curve is shifted upwards due to a loss of sensitivity.

When IHCs are damaged there is an overall loss of sensitivity and when both OHCs and IHCs are damaged hearing thresholds can be elevated by as much as 80 dB or more. Moore (2007) states that many forms of hearing loss are due to the loss of functioning OHCs, and that when IHCs are also damaged a more severe loss is experienced. When IHCs are completely non-functional the term ‘dead region’ is used to describe the total loss of the transduction mechanism. Functionally, the effect of damaged OHCs and IHCs results in hearing loss of varying degrees.

2.1.1 Types of Hearing Loss

Audiologists use a classification system (Figure 3) to describe the severity of hearing thresholds and have a number of descriptive categories for the types of hearing loss experienced by people (Katz, 2009). Hearing loss can be categorised as a conductive, cochlear or retrocochlear hearing loss. A conductive hearing loss is due to reduced sound transmission through the middle ear system. For example, it may arise from cerumen blocking sound transmission at the level of the external auditory meatus, or be related to malformed or damaged ossicles in the middle ear. Fluid and infection in the middle ear can also attenuate sound. Many forms of conductive hearing loss can be treated by medication (to resolve infections) or by surgery (Moore, 2007; Patuzzi, 2009; Pickles, 2008) .

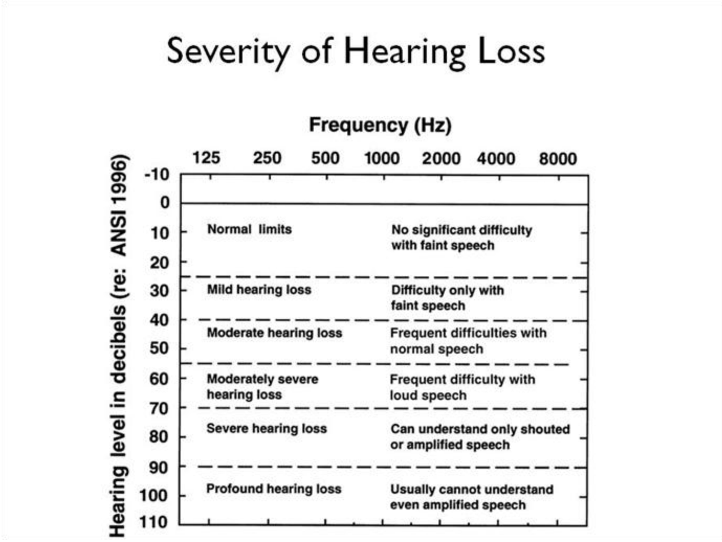

Figure 3. Classification of hearing level in decibels (ANSI, 1996).

Cochlear hearing loss results from damage to structures in the cochlea such as the hair cells. Exposure to acoustic trauma and ototoxic chemicals (such as antibiotics and chemotherapy drugs) can cause damage, as can autoimmune disorders, metabolic disturbances and some genetic factors. When both cochlear and neural structures are damaged the hearing loss is described as sensorineural (Moore, 2007; Patuzzi, 2009; Pickles, 2008).

When hearing loss is due to damage beyond the cochlea it is referred to as retrocochlear hearing loss. This occurs when the auditory nerve or any part of the higher pathways in the auditory system are damaged. One cause of retrocochlear hearing loss is an acoustic neuroma – a type of benign tumour that grows around the auditory nerve reducing the efficiency of the neural transfer of impulses to the auditory cortex (Moore, 2007; Patuzzi, 2009; Pickles, 2008).

2.1.2 Normal Hearing Defined

Normal hearing (NH) is generally defined as hearing thresholds that range from -10 dB HL to 20 dB HL across the listening frequencies of 250 Hz - 8,000 Hz which encompasses the important frequencies for speech understanding (500 Hz - 4 kHz) (Schlaunch & Nelson, 2009). In the field of audiology threshold information is obtained using pure tone audiometry (PTA) which is the gold standard for determining a person’s hearing sensitivity. International standard ISO 8253-1 ensures consistent practices are followed in measuring and classifying hearing loss (International Organisation for Standardisation, 2010). The two most commonly used measurements in audiometry are sound pressure level (SPL) and hearing level (HL). Threshold measures are recorded on an audiogram similar to the one shown in Figure 3 using dB HL. Pure-tone audiometry provides important information about the type of hearing loss and amount of loss, and frequency- specific information that assists in diagnosis and intervention (Schlaunch & Nelson, 2009).

2.1.3 Hearing Impairment Defined

Hearing impairment is an inability of an individual to hear sounds within the normal range of hearing (-10 dB to 20 dB HL). As shown in Figure 3, there are a range of categories of hearing loss. Each of these categories equates to varying degrees of disability and requires specific, targeted interventions in order to provide the person with access to intelligible speech understanding (Schlaunch & Nelson, 2009).

2.1.4 Prevalence of Hearing Loss

The World Health Organisation (WHO, 2006) has compiled worldwide statistics about hearing impairment. WHO states that based on 2005 information it is estimated that 278 million people worldwide have moderate to profound hearing loss in both ears and that this number is growing as the global population expands and life expectancies increase.

People with hearing loss can be grouped into three categories. The first category is those who develop a hearing loss from birth or in childhood due to congenital factors or a childhood illness that results in damage to their hearing system. Health professionals on average identify 140 children born with hearing loss each year in NZ (Ministry of Health, 2008).

In the middle years of life hearing loss can occur due to any number of events such as head trauma, otosclerosis (bony growth that affects the middle ear ossicles), Ménière's disease (associated with fluctuating hearing and balance problems) and viral infections, which all can cause sensorineural hearing loss. This age group also often shows signs of hearing loss due to noise exposure in the workplace. Noise induced hearing loss typically affects more men than women, and many of these individuals do not seek help until they are in their 60s (Dobie, 2008; Ministry of Health, 2008).

The third age category is people who develop an age-related hearing loss (presbycusis), which is a gradual loss of hearing that is attributed to a life-time accumulation of insults on their hearing system. Typically, the effects of presbycusis are first experienced by men around the age of 57 and women close to the age of 65 in NZ (Ministry of Health, 2008). Presbycusis is responsible for more cases of hearing loss than any other factor and occurs most frequently in this age group. On average people in this age group tend to wait six to eight years to seek help after first noticing problems with their hearing (Ministry of Health, 2008), and when they do seek assistance it is often only after the insistence of significant others such as a spouse or children (Hétu et al., 1993).

The U.S Department of Health and Human Services lists hearing impairment as the second most prevalent chronic condition associated with old age (Tesch-Römer, 1997). Wallhagen (2010) reports that hearing loss is becoming more prevalent in younger age groups and that as many as 77% of persons aged 60-69 years have high-frequency hearing loss which negatively impacts their communication and social activities.

2.1.5 Benefits of Amplification

A review of a number of studies by the American Academy of Audiology Task Force on the *Health-Related Quality of Life* (HRQoL) *Benefits of Amplification in Adults* (Chisolm et al., 2007; Chisolm et al., 2007) found that amplification improved adults HRQoL by reducing social, psychological and emotional effects of hearing loss. Early research by Mulrow, Tuley,& Aguilar (1992) also reported sustained social and communication benefits for a group of veterans who had been wearing hearing aids for one year. Research has shown that there are long term benefits in correcting hearing loss and using hearing instruments (Chisolm et al., 2007; Chisolm et al., 2007; Mulrow, Tuley, & Aguilar, 1992) . Providing people with information and a screening tool that assists them in monitoring their own hearing health can ensure people continue to enjoy an active social life.

2.1.6 Issue of Background Noise

Typically, people with a mild or moderate hearing loss can cope when listening to others in a quiet environment with just one person talking (Moore, 2007; Plomp & Mimpen, 1979b). As a person’s hearing loss worsens, even listening in quiet becomes challenging. The most common complaint for people with a cochlear hearing loss is their inability to understand speech in background noise (Killion, 1997; McArdle & Wilson, 2009; Moore, 2007; Plomp & Mimpen, 1979b). Moore (2007) notes that there is considerable controversy among researchers as to the reasons for the difficulty in understanding speech in background noise. One argument is simply that reduced audibility is the primary cause. Persons whose thresholds are elevated hear proportionally less of the speech spectrum than normal listeners (Dubno, Dirks, & Morgan, 1984; Moore, 2007; Plomp & Mimpen, 1979b). Others argue that the impact of noise reflects a reduced ability to discriminate sounds which are outside a person’s audible thresholds (Dubno et al., 1984; Moore, 2007; Plomp & Mimpen, 1979b). Irrespective of underlying cause, the fact remains that people with cochlear hearing losses have significant problems understanding speech in competing background noise (Carhart & Tillman, 1970; Killion, 1997; R. Wilson, 2004; R. Wilson & Weakley, 2004).

3 Hearing Tests

There are a number of ways in which audiologists can assess a person's hearing status in order to determine if they have a hearing loss. The gold standard is a behavioural evaluation using PTA to identify the degree, type and configuration of a hearing loss (ASHA, 1988; McArdle & Wilson, 2009). If a hearing loss is found, then appropriate recommendations can be made to ensure that a person achieves optimal access to auditory signals, given the degree, type and configuration of their hearing loss. This is the start of the process of helping a person come to terms with the changes in their hearing (Katz, 2009).

A range of other physiological tests is available to determine the health of the middle ear (e.g. immittance testing) and the status of the central auditory pathways (e.g. auditory brainstem test, acoustic reflex testing). Results of these tests add valuable information that is important in the management of the person's hearing loss (Katz, 2009).

While pure-tone audiometry helps to establish an individual's thresholds for hearing, it does not provide a definitive assessment of a person's ability to process complex speech stimuli (Katz, 2009; McArdle & Hnath-Chisolm, 2009; McArdle & Wilson, 2009). Thus a comprehensive hearing assessment usually includes a speech test such as a monosyllabic word test in quiet (e.g. PB-50; CID W-22; AB word list; NU No 6.). Researchers are now encouraging audiologists to routinely assess a client's ability to understand speech in noise, as this is often their biggest complaint (Carhart & Tillman, 1970; Dubno et al., 1984; McArdle & Wilson, 2009). One of the best ways to assess an individual's ability to hear in a noisy environment is with a speech-in-noise test (Killion & Niquette, 2000; McArdle & Hnath-Chisolm, 2009; Plomp, 1986; Smits, Kramer, & Houtgast, 2006; Taylor, 2003). Such tests include the QuickSIN and the Hearing in Noise – Sentences Test (HINT).

McArdle and Wilson (2009) reported in their 2005 research study that speech-in-quiet tests were not good predictors of an individual's ability to perform well in speech-in-noise tests. Of the 283 participants who scored above 80% on the speech-in-quiet tasks, only five participants scored in the normal range on the speech-in-noise tasks. This illustrates the value of including speech in noise tests, as they are more challenging for people with mild to moderate cochlear or neural disorders as well as for older individuals who may perform well in quiet environments (Killion & Niquette, 2000; McArdle & Wilson, 2009; Plomp, 1986).

3.1 Self – Report for Hearing Loss

Studies have shown that the percentage of people with hearing impairment that wear hearing aids is very low, resulting from concerns about stigma and cosmetic appearance, lack of awareness of loss, a negative view of ageing and concerns about the negative attitudes of other people (Brooks & Hallam, 1998; Dalton et al., 2003; Tesch-Römer, 1997; Wallhagen, 2010). Part of the reason for not seeking intervention is that people underestimate their hearing loss as they age (Helvik et al., 2006a; Nondahl et al., 1998). It has been found that a screening tool that is objectively measured is more accurate than a questionnaire in providing information about a person's hearing ability (Helvik et al., 2006a; Nondahl et al., 1998). When people use a self-report questionnaire such as the Hearing Handicap for the Elderly – screening version (HHIE-S) they tend to underestimate their hearing loss. Nondahl et al. (1998) conducted a study examining the accuracy of self-reported hearing loss using the HHIE-S with four additional questions that asked the person to evaluate their hearing. The reported hearing ability was then compared to the results of a hearing test. This study reported that the older adults (65-92 years) were less accurate in reporting hearing loss (under-estimated) than younger participants. The study found that for 0.5 – 4 kHz mild hearing loss (>25 dB HL) the questionnaire had a sensitivity of 71% and a specificity of 71%. The Blue Mountains Hearing Study (Sindhusake et al., 2001) compared a single question asking people 'Do you have difficulty hearing and understanding most things people say, without seeing their face and lips?' to the HHIE-S. Sindhusake et al. (2001) reported that the question was more effective in identifying mild hearing loss while the HHIE-S was more effective in identifying people with moderate hearing loss. The Blue Mountains Hearing Study reported that the self-report for 0.5 – 4 kHz mild hearing loss (>25 dB HL) had a sensitivity and specificity of 78% and 67% respectively. Helvik et al. (2006) reported that the correlation between an objectively measured hearing impairment and a person's own assessed status of their hearing (a Pearson's r of 0.36) was less than they expected. While different epidemiology studies have reported varying effectiveness for their screening questions they have generally found that older adults tend to believe that hearing loss is part of the ageing process and simply do not want to admit any deficit. Older adults also tend to compare their own functioning to others in their age group and hence have a skewed sense of what is 'normal' hearing. People do not see hearing loss as a health problem that should receive attention in the same way that blurred vision requires correction with spectacles (Brooks & Hallam, 1998; Dalton et al., 2003; Nondahl et al., 1998). This is in part due to a lack of awareness and education about the negative impact on mental health that auditory deprivation can cause a person (Brooks & Hallam, 1998; Dalton et al., 2003; Nondahl et al., 1998).

3.2 Effectiveness of Screening as a Tool for Intervention

Overseas health care programmes have recognised the importance of establishing routine screening of hearing loss in older adults. Currently there are no routine hearing screening tests for the general adult population available in NZ. How then can adults be made more aware of the need to regularly check their hearing status and have easy access to such a health service? A number of researchers have examined the effectiveness of hearing screening tools. Yueh et al. (2008) examined the long-term effectiveness of screening programmes for older veterans using two specific screening tools – a handheld tone emitting otoscope (*Audioscope, Welch-Allyn Inc., Skaneateles Falls, NY*) that emitted tones at 20, 25 and 40 dB HL across the important speech frequencies at (500 – 4,000 Hz), and a questionnaire. The researchers used the screening version of the Hearing Handicap Inventory for the Elderly. The questions are designed to measure the degree of social impact that a person's hearing loss is perceived to have on their daily life. The study reported that the questionnaire was a less efficient intervention tool with their study population (older veterans) than the use of the screening otoscope. The functional hearing test resulted in more veterans accepting the need for a hearing aid. This study illustrates the potential positive effect that providing a functional test (physical experience) such as a hearing screening programme may have in changing attitudes about seeking intervention (Yueh et al., 2010). A screening test should also be simple, safe, acceptable and cost effective (Schow, 1991; Smits, Kapteyn, & Houtgast, 2004).

3.2.1 The Digit Triplet Test as a Hearing Screening Tool

The Digit Triplet Test (DTT) (Elberling, Ludvigsen, & Lyregaard, 1989) is a hearing screening tool that can be adapted for use on a telephone or over the internet (Smits et al., 2004), making it widely accessible by people from all walks of life. Developing a hearing screening tool such as the DTT that can be accessed via these media is likely to increase the convenience for people, reduce health service costs, provide people in isolated areas with more timely health care service, and help to reduce the stigma of hearing loss by normalising the issue (Griffiths, Lindenmeyer, Powell, Lowe, & Thorogood, 2006).

The HEARCom project in the European Union saw the development of a number of DTT tests in member countries. Creating a hearing screening test that is compatible with the telephone and /or internet requires using speech material that is easy to score and produces a steep psychometric slope. The traditional sentence-in-noise material is too complex for an automatic programme to score. One solution is to use closed-set speech material, for example digits, and follow the adaptive procedure used by Plomp and Mimpon (1979a).

3.2.2 The Adaptive Procedure

An adaptive procedure involves taking the response to the stimulus for one trial and using that response to determine the next stimuli. The advantage of this method of testing is that it is simple, highly efficient and robust. The adaptive procedure is also reliable even when using a small sample size and is generally free of other factors that could influence the responses (Levitt, 1970).

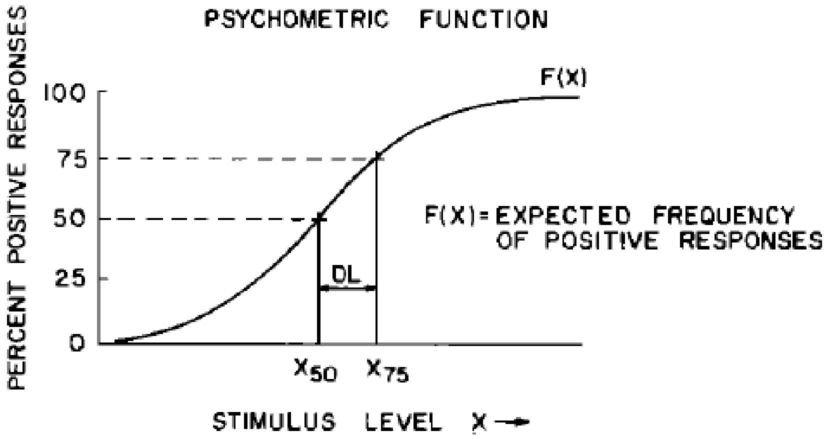

Figure 4. Typical psychometric function. The curve shows the expected frequency of positive responses in a typical experiment. Source: (Levitt, 1970)

Plomp and Mimpen (1979b) researched the accuracy of speech-recognition thresholds (SRT) for sentences-in-noise using a simple adaptive up-down test procedure. The adaptive procedure used a 2 dB step size which adjusted the signal-to-noise in relation to correct and incorrect answers to determine the 50% intelligibility score for the speech material presented. This study reported a standard deviation of only 1 dB for the 13 sentences used when this limited test set was compared to longer test batteries in establishing the 50% speech reception threshold (SRT). This compared favourably with other research and showed that an adaptive test procedure with limited speech material resulted in very accurate SRT values (Plomp, 1986). Wagener and Brand (2005) examined the influence of measurement procedures and concluded that results for SNR are not affected by the adaptive procedure used. Therefore, an adaptive procedure that uses fixed noise level compared to the same procedure using fixed speech levels will provide essentially the same result. Plomp (1986) (as cited by Smits 2006) found ‘that the SRT of a listener does not depend on absolute presentation level but only on the ratio between speech and noise’. Smits (2006) concluded that a telephone or computer could be used to present a screening speech-in-noise test because no exact control over the presentation level was necessary. The noise and signal could be made from the same speech material and therefore maintain the SNR of the test. As the telephone transmits only a narrow band of speech frequencies (300 -3400 Hz), the signal-to-noise ratio needs only to be set at a ratio suitable for the telephone and would not require any other acoustic adjustments (Smits, 2006).

3.2.3 Use of Digits as Stimuli in Screening Tests

The use of digits as a speech screening material has a long history dating back to nineteenth century German otologists who used digits for diagnostic hearing tests (Rudmin, 1987). In the 1920s the Western Electric No. 4A Speech Audiometer battery of tests used numbers as part of the speech test material (Smits, 2006). Since that time a number of studies have used digits as speech material (Elberling et al., 1989; Jansen, Luts, Wagener, Frachet, & Wouters, 2010; Ozimek, Kutzner, Sek, & Wicher, 2009; Smits et al., 2004; Wagener, Bräcker, Brand, & Kollmeier, 2006; R. Wilson & Weakley, 2004). Rudmin (1987) reported that digits were the best speech material to use when testing speech recognition thresholds (SRT) for non-native English speakers in Canada because they were very familiar with these words. Thorndike and Lorge, as cited by Rudmin (1987), reported that numbers are among the 500 most frequently used words in English. More recent research also confirms that numbers are frequently used words in the English language (Leech, Rayson, & Wilson, 2001) and are therefore very suitable to use as speech testing material. Digits have also been found to have the steepest articulation function and are the most intelligible in noise (Ramkisson, Proctor, & Lansing, 2002).

Each English language digit below ten has either one syllable, or two syllables in the case of ‘seven’ and ‘zero’. By selecting digits that have the same number of syllables the homogeneity of the speech material used can be maintained and the intelligibility function increased. A number of other digit screening tests have taken this into consideration when determining which digits to use in their screening test (Elberling et al., 1989; Jansen et al., 2010; Ozimek et al., 2009; Smits et al., 2004). For example, the German and Dutch tests exclude digits ‘seven’ and ‘nine’ which are both disyllabic to ensure the material remained homogeneous (Smits et al., 2004; Wagener et al., 2006). However, Ozimek et al. (2009) included a combination of monosyllabic and disyllabic digits in their test because the Polish language contains six disyllabic digits and it was not practicable to exclude these digits, leaving only four monosyllabic digits. Ozimek et al. (2009) found that in the case of the Polish language, the type of digit (monosyllabic or disyllabic) did not significantly influence the SRT of the speech material.

Smits and Houtgast (2007) examined continuous noise and interrupted noise when measuring triplet SRT and reported that for the digit triplet test the use of continuous noise was very efficient at screening for hearing impairment. Continuous noise has been used in a number of hearing screening tests using digits that have since been developed (Elberling et al., 1989; Jansen et al., 2010; Smits et al., 2004). Because the signal and the noise are both speech, a non-calibrated medium such as the telephone or internet can be used to present the test. The digit test is quick and easy to use. Existing versions of the DTT in other languages can typically be completed in a few minutes.

The DTT measures a patient's ability to identify speech in background noise and provides a result that can be used to estimate the status of their hearing. It is well known that hearing impaired people find it extremely difficult to understand speech in noise (Elberling et al., 1989; Jansen et al., 2010; Ozimek, Kutzner, Sek, & Wicher, 2007; Ozimek et al., 2009; Pickles, 2008; Smits et al., 2004). The DTT has the potential to separate NH individuals from those with a significant hearing loss. The results of the participant's responses are interpreted by the computer programme (Jansen et al., 2010; Ozimek et al., 2009; Smits et al., 2004), and based on a predetermined SNR cut-off value (which differs for telephone and broadband test delivery methods) the user will receive a message that provides information on their hearing ability. A number of countries have already developed screening tests using digits Table 1). The Dutch version of the DTT has been in use since 2004 and by 2005 had collected over 160,000 responses (Smits & Houtgast, 2005). The French telephone digit triplet test was launched nationwide in February 2009 and in the first month they recorded 20,000 phone calls (Jansen et al., 2010).

Table 1. Languages with a Digit Triplet Test for Telephone

Language	Study by
Danish	Elberling et al., 1989
Dutch	Smits et al., 2004
English (Australian)	Golding et al., 2007
English (Canadian)	Rudmin, 1987
English (UK)	Hall, 2006 unpublished thesis cited in Ozimek et al., 2007
English (USA)	Ramkissoon et al.,2002; Wilson and Weakley, 2004
French	Jansen et al., 2010
German	Wagener et al., 2005a
Polish	Ozimek et al., 2009

Source: (Jansen et al., 2010; Ozimek et al., 2007; Smits et al., 2004; Wagener et al., 2006).

3.2.4 The Value of a Hearing Screening Test

A great deal of public health data may be gathered through the provision of a hearing screening tool such as the DTT. The test may be accessed by the public via a telephone (cell phones are excluded at present) or via the internet. The HEARCom D-1-4b report (HEARCom, 2006) identified a number of advantages for delivering a health service in this manner:

1. It provides a person with quick and easy assessment of their own hearing performance.
2. It provides general practitioners with an inexpensive way to check a patient's hearing ability which does not involve investment in expensive equipment or the training of staff.
3. It raises public awareness about hearing impairment and treatment options.
4. Using the internet provides a platform whereby specific guidance about hearing protection, interventions and professional services within the person's location can be provided.
5. Using the telephone means that people who lack access to the internet due to a range of reasons can still obtain information about their hearing.
6. Both delivery methods (internet and telephone) have the potential to gather public health information that can be used to inform government funding and health policy related to hearing, and possibly provide data to examine trends in hearing loss that are occurring within NZ society.

4 Statement of the Problem

As the adult population ages more people will develop a hearing disability that will affect their daily lives, psychological health, work situation and personal relationships (Ministry of Health, 2008). This study describes the development and trial of a DTT recorded using a native speaker of NZ English. Approval for the study was obtained from the University of Canterbury Ethics Committee and is contained within **Appendix I**.

5 Development of Speech Material for the DTT

5.1 Analysis of Female Speaker's Voice

NZ English has unique vowels and pronunciation (Watson, Harrington, & Evans, 1988; Watson, Maclagan, & Harrington, 2000). It is therefore preferable to have a separate NZ English version of the DTT rather than a recording from another form of English. Before recording the digits, the 26 year old female speaker's voice was analysed to ensure that she could be classified as a native speaker of NZ English. The speaker was asked to repeat the following list of words three times:

Heed, hid, head, had, hard, hod, horde, who'd, hood, heard, hud

These words contain the vowel sounds that were analysed to confirm the speaker's accent (Maclagan & Hay, 2007). The speech was analysed for placement of formant 1 (F_1) and formant 2 (F_2) using the acoustic analysis software, Praat [1](Boersma & Weenik, 2010). The average formant values measured from the female speaker were compared to NZ data from 1994 (Figure 5) by Maclagan & Hay (2007).

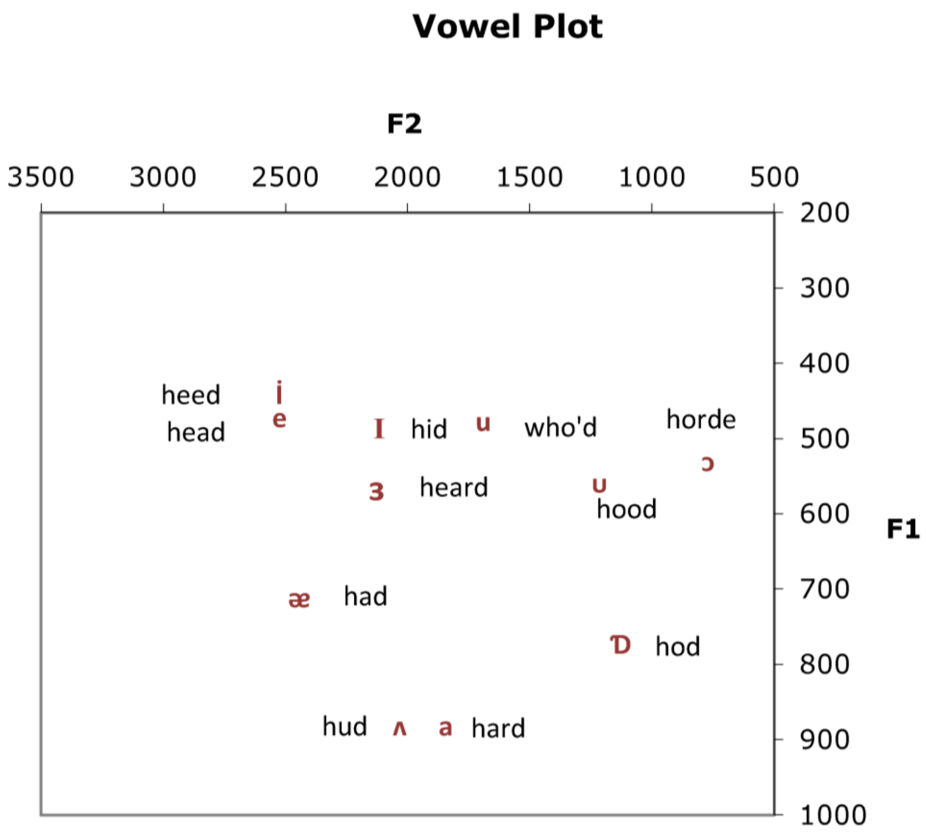

Figure 5. Vowel chart for NZ English speakers born in 1975, and recorded in 1994. The figure has been adapted to include word alignment with matching vowel sounds. *Source:* (Maclagan & Hay, 2007)

1. Praat is available from http://www.fon.hum.uva.nl/praat/.

The comparison of results with Figure 5 data showed that the 26 year old female speaker selected to record the DTT speech stimuli had an authentic and representative NZ accent (Figure 6) as judged by Assoc. Prof. Margaret Maclagan, an expert linguist who specialises in NZ English.

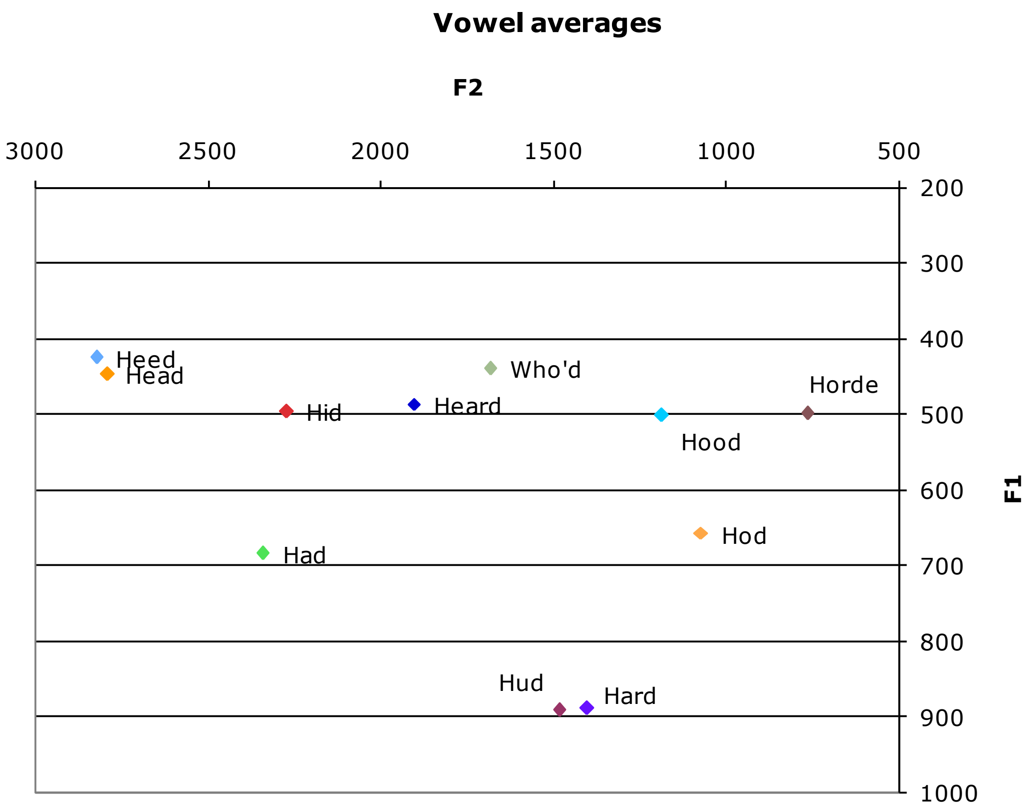

Figure 6. Vowel averages (F1 and F2) recorded for the female native NZ English speaker used to create the NZ Digit Triplet Test 2010.

5.2 Recording the Digit Speech Material

The DTT speech material was recorded using the voice of the 26 year old female who had been identified as having a representative NZ accent. The triplets were recorded three times to ensure a natural intonation without co-articulation. The recordings were made in a double-walled sound-proof booth using a head-mounted microphone positioned approximately five centimetres from the speaker's mouth. Her speech output was digitally recorded using Sony Sound Forge (v9.0, Madison Media Software, Madison, WI) at a sample rate of 44.1 kHz and saved in waveform audio file format (.wav). The announcement 'The digits' was recorded separately several times, and the recording that was subjectively judged 'the best' by the author was selected and used throughout the testing.

Each of the 24 digit recordings was played via an InSync Buddy 6G USB soundcard and Sennheiser HD 280 headphones placed on a Brüel & Kjær Head and Torso Simulator Type 4128-C (Brüel & Kjær, Nærum, Denmark). The sound level of the headphone output was measured in dB (A) by a laptop running Brüel & Kjær Pulse Labshop v11.1. Each digit sound file was then adjusted so that all were at an equal intensity level.

5.3 Noise Synthesis

The noise sample used in the DTT was created by superimposing the 24 digit recordings 10,000 times using an automated process. The stimuli presented in the DTT therefore consisted of noise and speech that had identical spectral components, as illustrated in Figure 7. This means that the SNR of the stimuli is maintained when filtered as the signal and noise are equal (Jansen et al., 2010; Ozimek et al., 2009; Smits et al., 2004). This then allows a digit test to be transmitted via broadband or telephone without the SNR being affected. Within reasonable limits, any changes to the presentation level of the test via headphones or speakers by users at home will therefore not alter the effectiveness of the DTT to determine if that person has passed or failed the hearing screening test (Hawkins & Stevens, 1950; Smits et al., 2004). The level of the background noise for the normalisation phase of the present study was set at a constant 65 dBA, while the level of the signal was varied to alter the signal-to-noise ratio.

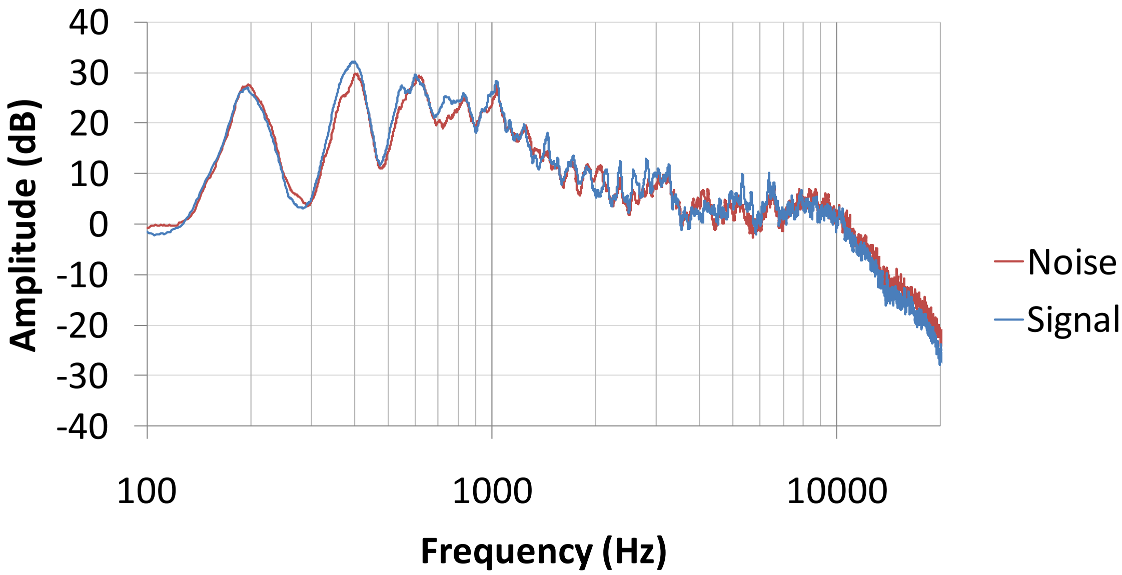

Figure 7. The amplitude spectra of the speech and noise components of the digit triplet test overlaid on one another.

5.4 Software

The technique of concatenating the speech files to form the stimuli was based on that used by HEARCom, but was performed by custom-written software.

Two programmes were used in the study. The first programme was for calculating psychometric data for the individual digits to inform the normalisation process, as described below. The second programme was the UC-DTT module incorporated into the University of Canterbury Adaptive Speech Test platform, or UCAST. This programme was used to deliver the DTT test itself in order to assess the equivalence of the test lists, and to establish normative data for NH and hearing impaired (HI) listeners. Both of these programmes were written by Dr Greg O'Beirne, Department of Communication Disorders, at the University of Canterbury.

5.5 Test Material Setup

There were 512 (8 x 8 x 8) possible combinations of the 24 recorded triplets, but this included combinations which would have resulted in repeated presentations of the same digit within a triplet, such as 1-1-1 or 1-1-2 or 1-2-1. Such combinations were removed, leaving 336 possible combinations remaining. Of these 336 triplet combinations, those selected for the final version of the test needed to be of equivalent difficult so as to ensure the reliability of the test (Ozimek et al., 2009; Smits & Houtgast, 2007). The speech material was therefore subjected to two normalisation processes. The first process gathered data to produce a psychometric function for each digit in each position. The second process combined the digits with the steepest psychometric functions into triplet combinations that then had their slope of the psychometric function for intelligibility evaluated. The final phase involved testing ten DTT lists to determine the slope for each list and to check the variability of results for each list to ensure all lists provided similar test results. The signal-to-noise ratios (SNR) used throughout the normalisation testing were -20.0; -17.5; -15.0; -12.5; -10.0; -7.5; and -5.0. The final DTT test used SNR of -16 to -2 dB. The testing was conducted in a single sound-proof booth (the GNResound Booth 2 located in the University of Canterbury's Rutherford Building). The noise presentation level was fixed at 65 dB SPL for our test. This is the same noise level used in a number of other DTTs, while other DTTs used slightly different levels of noise stimulus (Table 2). The software programme concatenated the announcement 'The digits.' and the three digits, with each of the four segments lasting around 919 ms. A period of 500 ms of silence was added to the beginning, and a further 200 ms of silence was added to the end, giving a total sample length of 4375 ms. A linear ramp of 50 ms was used for the onset and offset of the noise stimulus. The digit speech material was created so the test presentation sounded natural, with pauses and level intonation. For example, the triplet 3-1-6 was understood by participants to mean ‘The digits three-one-six’ (not as ‘The digits three hundred and sixteen’).

Table 2. Current DTT parameters

County (Author, Year)	Participants - Normalisation I	Presentation of digits	Audiometric Thresholds 250 Hz - 8000 Hz	Constant Noise	Listening Condition	SNR settings
Netherlands (Smits, 2004)	n = 80	285 lists (lists contained 23 triplets)	≤ 15 dB	73 dB A SPL	Telephone	- 10 dB starting level 2 dB step sizes
German (Wagener et al., 2006)	n = 15	6 * 27 *2 = 324 presentations	Not stated	65 dB SPL	Sennheiser HDA200	12.0; -10.5 and -9.0 dB
Polish (Ozimek et al., 2009)	n = 50	160 digit triplets * 7 SNR	≤ 15 dB	70 dB SPL	Sennheiser HD 580	-14.5; -13.0; -11.5; -10.0;-8.5; -7.0 and -5.5 dB
French (Jansen et al., 2010)	n = 30	14 test lists (each SNR twice)	≤ 20 dB	65 dB SPL	Sennheiser HDA200	-17.9; -15.9; -13.9;-11.9:--9.9, -7.9: and -5.9 dB

6 Normalisation Procedure I

6.1 Introduction

The speech material which had already been normalised for intensity level needed to be tested to determine the intelligibility function for each single digit in each triplet position. The monosyllabic digits 1 to 9 were presented a number of times to NH listeners. The 8 digits were presented in each triplet position over 7 SNRs for a total of 168 presentations i.e. 8 x7 x 3. This provided the data needed to establish an intelligibility function for each single digit in each triplet position. By establishing the psychometric function for each digit in each position the most sensitive (digits with the steepest slope) could be selected to create more sensitive triplet combinations. This would then enable a more sensitive DTT to be created. The testing was conducted in the GNResound Booth 2 located in the University Canterbury’s Rutherford Building.

6.1.1 Participants

A total of 22 NH participants (16 female and 6 male) aged from 18 – 69 years with an average age of 33 years participated in this phase of the study (Table 3). Each participant was tested in a sound booth after having signed a consent form to participate in the study. Both eardrums were visually inspected using an otoscope (a specialised ear torch) to determine ear health. Next, participants completed a hearing screening test to determine their eligibility for the study. This comprised a pure-tone audiometry (PTA) test to establish that the participant's hearing sensitivity was in the normal range (≤ 20 dB) across the frequencies 250 Hz to 8 kHz, a range which includes the important speech frequencies of 500 Hz – 4 kHz. Those participants that passed the PTA test criteria then listened to the 168 triplet digit presentations using Sennheiser HD 280 pro headphones.

Table 3. Age and sex distribution of participants for Normalisation Procedure I.

	Age Range				
	18-29	**30-39**	**40-49**	**50-59**	**Over 60**
Female	7	2	5	1	1
Male	4	1	1	0	0
Total	11	3	6	1	1

6.1.2 Method

Participants were instructed to use the computer keyboard number pad to enter the three digits they heard. They were instructed that they would hear 168 presentations in total and that the next presentation would not occur until they had entered a 3 digit answer for the current presentation. The computer screen provided a graphical user interface for data input (Figure 8) so that participants could see the digit they had entered and correct any errors if they accidentally keyed in the wrong digit. In one corner of the screen the number of test presentations completed was displayed. The participants were not told that the digits zero and seven were omitted from the test. Participants were instructed to guess if they were unsure what was said. This phase of the test took on average 19 minutes (± 2 min) (range: 16 -24 minutes) for the participants to complete.

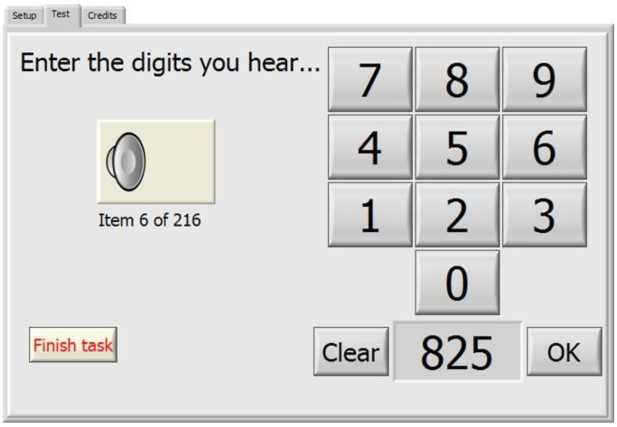

Figure 8: Computer screen shot of the graphical user interface.

6.2 Results of Normalization Procedure I

The 22 participants provided a pool of data that was used to calculate a psychometric function for each digit presentation in each position, across each SNR used during the test, e.g. 3 x 8 x 7 = 168 presentations. The analysis involved identifying each correct response for the digits presented. The mean for the responses was calculated and the slopes for each digit position were plotted.

The following logistic function was used to analyse the data and determine the intelligibility level for each digit:

$$\mathrm{SI}\,(\mathrm{L}) = \frac{1}{A}\left(1 + \mathrm{SI}_{\,\mathrm{max}}\,\frac{A - 1}{1 + \exp\left(-\,\dfrac{\mathrm{L} - \mathrm{L}_{\,\mathrm{mid}}}{s}\right)}\right)$$

with $\mathrm{L}_{\,\mathrm{mid}}$: speech level of the midpoint of the intelligibility function.

S: slope parameter. The slope at $\mathrm{L}_{\,\mathrm{mid}}$ is given by $\dfrac{\mathrm{SI}_{\,\mathrm{max}}\,(A - 1).}{4\,A\,s}$

Equation 1: Function relating speech intelligibility to signal level. Source: (Wagener et al., 2006).

For each of the 168 digit triplet presentations separate intelligibility thresholds for each digit at each SNR were obtained. The result yielded a mean digit psychometric function midpoint (L_{mid}) of -14.4 dB SNR (± 2.6 dB) and a mean slope of 16%/dB SNR (± 5.6%/dB).

The measured psychometric functions are shown in Figure 9. The psychometric function midpoints were then used to calculate level corrections for each digit so that each digit had an L_{mid} of -14.5 dB SNR. The mean magnitude of the corrections applied to the digits was 2.2 dB (± 1.4 dB). The hypothetical psychometric functions following these corrections are shown in Figure 10.

6.3 Discussion of Results of Normalisation Procedure I

There was a degree of variation between the psychometric functions recorded for the digits during the first stage of normalisation. For example, in the first position the psychometric function for the digit ‘four’ had an L_{mid} of -11.4 dB SNR, while the function for the digit ‘two’ had an L_{mid} of -16.3 dB SNR (Figure 9).

The measured A-weighted sound level of both recordings (and of *all* the digit recordings) was the same. Further examination of the acoustic stimulus failed to reveal any explanation for this observation at this stage of the digit normalization process. The sound files for the digits ‘four’ and ‘two’ was acoustically balanced in the same manner across the three triplet positions. One possible explanation is that the word ‘four’ consists of an unvoiced high frequency ‘f’ and only two phonemes, which may have contributed to a reduced SRT_n (std = 4.1, slope at midpoint 5.32%/dB). In comparison the digit ‘two’, which also has two phonemes, but has a voiced ‘t’ resulting in the digit ‘two’ having one of the steepest slopes (std = 0.81, slope at midpoint 26.88%/dB) (Figure 9).

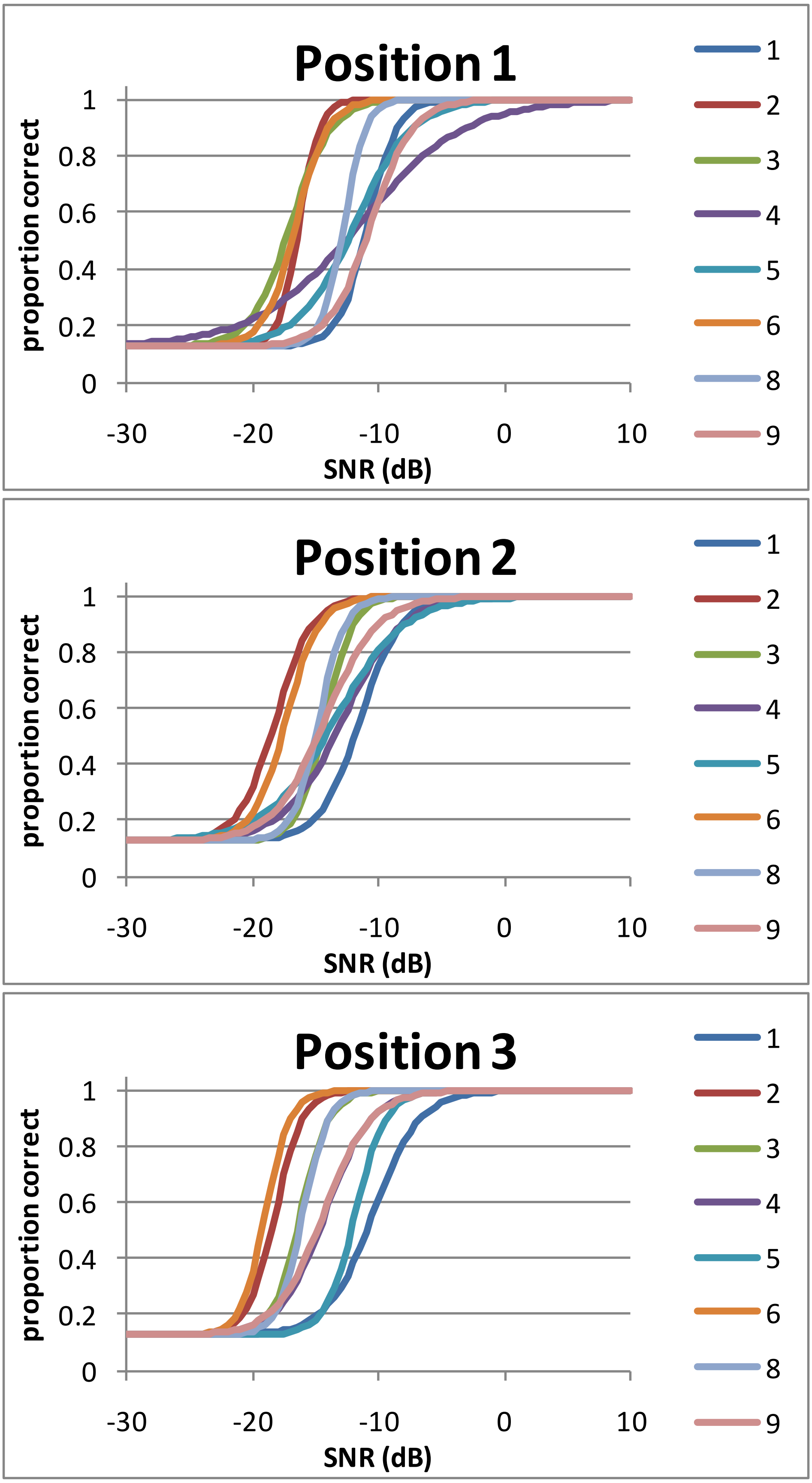

Figure 9. The psychometric functions for each digit in each position prior to normalisation.

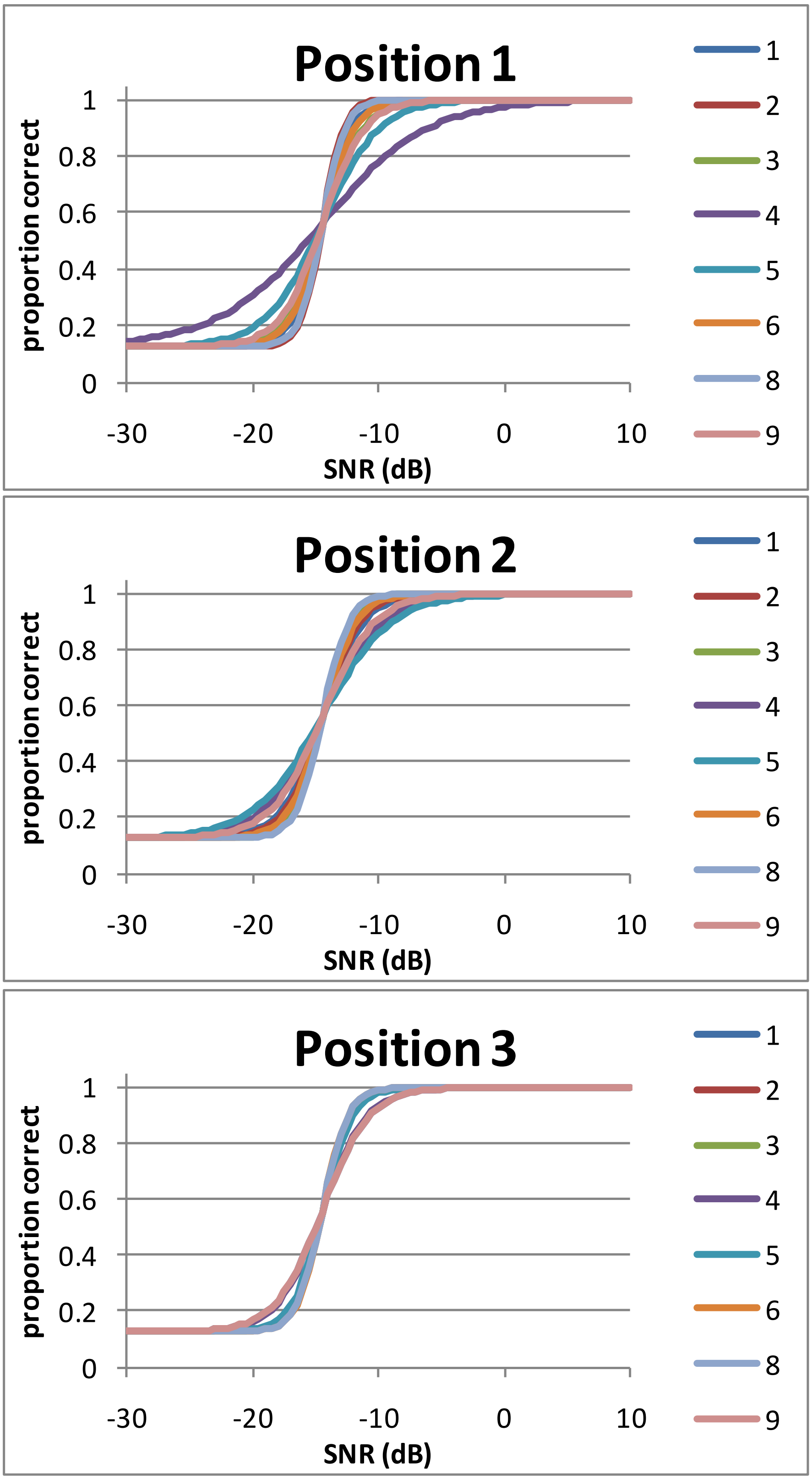

Figure 10. The hypothetical psychometric functions for each digit in each position after correction of each digit's level so as to achieve a consistent L_{mid}. A second normalisation procedure was then undertaken to confirm that these hypothetical psychometric functions approximated reality.

6.4 Generation of the DTT Lists

Another aim of this first normalisation process was to provide information on the slope of the digits in each of the positions that would allow the production of 10 equivalent lists of digits, each consisting of 27 presentations. In this case, equivalency was defined in terms of the L_{mid} and slope at the midpoint, with the aim of ensuring the sensitivity of the test determining the SRT_n. Each DTT list consisted of 27 x 3 normalised digits used to create triplet digit combinations. To maximise the slope of each list while including as many of the digits as possible, a computer programme was developed by Dr Greg O'Beirne that assigned a weighting to each digit based on its slope. The digits in each position with the maximum and minimum slopes were identified, and these were assigned 'weightings' of 175% and 25% respectively. All other digits were assigned weightings between these two extremes, based on their slopes. The programme then constructed sets of triplets such that the digit with the highest slope in each position occurred 75% more frequently than the hypothetical average and the digit with the lowest slope occurred 75% less frequently, with the frequencies of the other digits in between. The process resulted in ten lists that had a hypothetical average triplet slope of 18.7%/dB (± 0.1 dB) with an average standard deviation of the slopes within each list averaging ± 1.7 dB (Table 4). A total of 216 digit triplets were selected to form 10 digit triplet test lists of 27 triplets (Figure 15).

Table 4. Summary of the hypothetical (calculated) slopes of the triplets in each of the ten test lists.

	List 1	List 2	List 3	List 4	List 5	List 6	List 7	List 8	List 9	List 10	*Mean*	*Std Dev*	*Max*	*Min*
Average slope	**18.6**	**18.6**	**18.6**	**18.7**	**18.8**	**18.8**	**18.6**	**19.0**	**18.7**	**18.5**	*18.7*	*0.1*	*19.0*	*18.5*
Std Dev	**1.8**	**1.7**	**1.5**	**1.6**	**1.5**	**1.9**	**1.8**	**1.8**	**1.9**	**1.7**	*1.7*	*0.1*	*1.9*	*1.5*
Max slope	**21.5**	**21.8**	**21.5**	**21.1**	**21.1**	**21.8**	**21.8**	**21.8**	**20.9**	**21.5**	*21.5*	*0.3*	*21.8*	*20.9*
Min slope	**15.4**	**16.0**	**16.1**	**15.6**	**15.8**	**15.6**	**15.1**	**16.0**	**15.0**	**15.6**	*15.6*	*0.4*	*16.1*	*15.0*

The second normalisation process would allow confirmation of the hypothetical data in Table 6 and establish the equivalency of the performance of the 10 generated lists.

7 Normalisation Procedure II

7.1 Introduction

To confirm the psychometric functions predicted following the level adjustment to each digit, and to establish the equivalency of the performance of the 10 generated lists, a second normalisation process was conducted. This phase involved the re-evaluation of the digit in a triplet function to reduce the variance of both the L_{mid} and slope measures. This step meant that generating a digit triplet from normalised digits should improve the slope of the triplet's psychometric function and improve the sensitivity of the test.

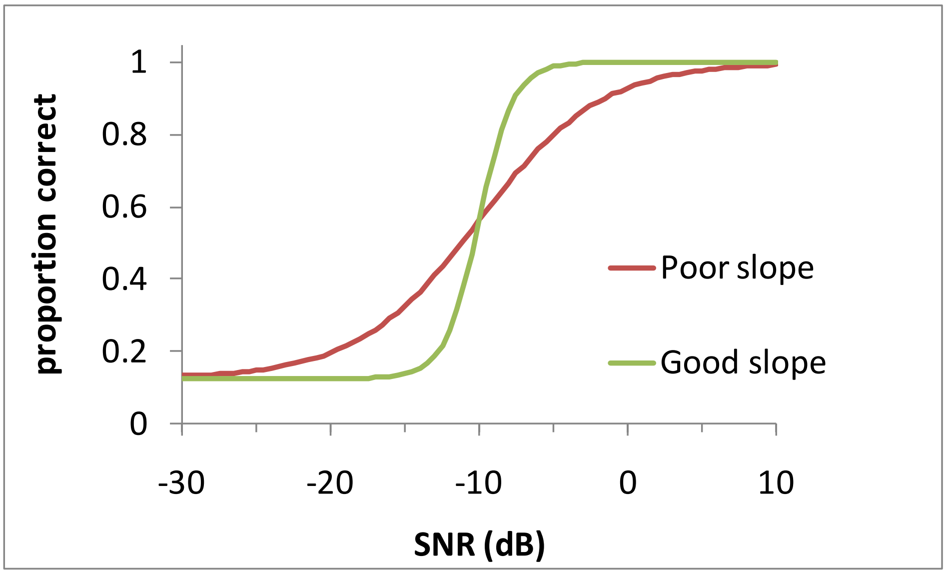

Figure 11. Illustration of poor and good digit slope. The steeper the slope the better the sensitivity.

7.1.1 Participants

A total of 21 normal-hearing participants (18 female and 3 male) aged from 18 - 69 years with an average age of 41 years participated in this phase of the study. Each participant listened to two of a total of ten possible lists of 27 digit triplets at each of four different SNRs for a total of 216 presentations, e.g. 4 SNR x 2 lists x 27 digits (Table 5). The SNRs were chosen to be equally spaced around the hypothetical post-normalisation L_{mid} of -14.5 dB SNR, and were as follows: -16.8; -15.2; -13.8; -12.2. The mean test duration was 25 ± 3 minutes (range: 20 – 31 minutes).

Table 5. Age and sex distribution of participants in normalisation procedure II.

	Age Range				
	18-29	**30-39**	**40-49**	**50-59**	**Over 60**
Female	3	2	8	4	1
Male	2	0	1	0	0
Total	5	2	9	4	1

7.1.2 Method

Participants were instructed to use the computer keyboard number pad to enter the three digits they heard. They were instructed that they would hear 216 presentations in total and that the next presentation would not occur until they had entered a 3 digit answer for the current presentation. The graphical user interface (Figure 8) allowed participants to see what digit they had entered and to correct errors in their typing. In one corner of the screen the number of test presentations they had completed was displayed. The participants were not advised about any digits omitted from the test, namely zero and seven. Participants were instructed to guess if they were unsure what was said.

7.2 Results of Normalisation procedure II

The results of this second normalisation process confirmed that the variance of both the L_{mid} and slope measures for the digits had been reduced. The psychometric functions for the normalised digits had a mean L_{mid} of – 13.7 dB SNR (± 1.0 dB) and a mean slope of 15% dB SNR (± 3.7% dB). (Figure 13)

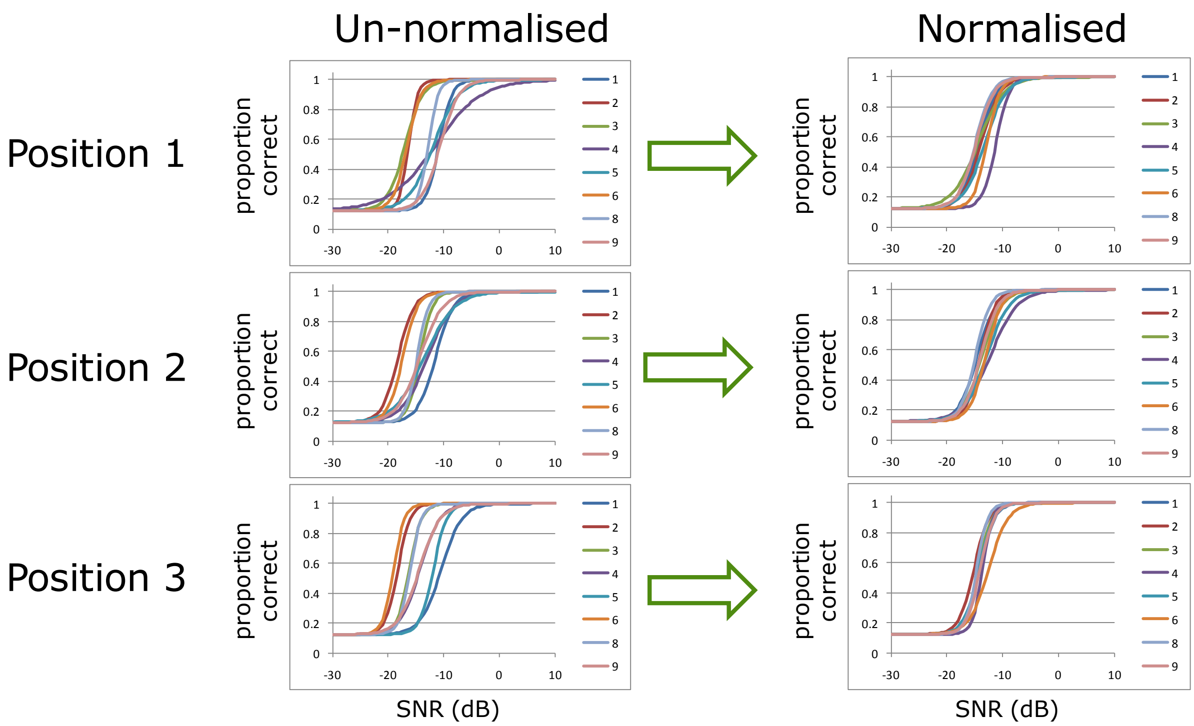

Figure 12. Results for the second normalisation process confirmed that the level adjustments for the digits had had the intended effect on their psychometric functions.

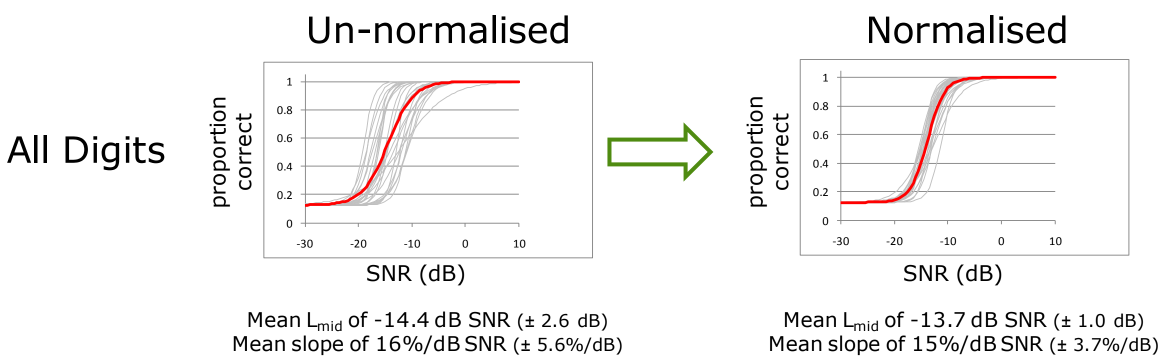

Figure 13. The data from Figure 12 collapsed into a single plot. The reduced variance of both the L_{mid} and slope measures is visible.

7.3 Discussion of results for Normalisation Procedure II

The psychometric evaluation of each triplet aimed to improve the sensitivity of the test by reducing the standard deviation of the L_{mid} of the digits in each triplet position. This was achieved, as shown in Table 6.

Table 6. Comparison of Normalisation I to Normalisation II and resulting changes to the mean and standard deviation of the L_{mid} values for each digit triplet in each of the 3 positions.

		Normalisation I (dB)	Normalisation II (dB)	Degree of Change (dB)
All Positions				
	Mean	-14.32	-13.75	-0.57
	StDev	2.62	0.96	1.66
	Mean + 1 SD	-11.70	-12.79	1.09
	Mean - 1 SD	-16.94	-14.71	-2.23
Position 1				
	Mean	-13.40	-13.62	0.22
	StDev	2.72	1.23	1.49
	Mean + 1 SD	-10.68	-12.39	1.71
	Mean - 1 SD	-16.12	-14.85	-1.26
Position 2				
	Mean	-14.55	-13.59	-0.96
	StDev	2.23	0.88	1.35
	Mean + 1 SD	-12.32	-12.71	0.39
	Mean - 1 SD	-16.78	-14.47	-2.30
Position 3				
	Mean	-15.01	-14.03	-0.98
	StDev	2.94	0.78	2.16
	Mean + 1 SD	-12.07	-13.25	1.18
	Mean - 1 SD	-17.95	-14.81	-3.13

7.4 List Equivalence Results

The results were also analysed at a list level, enabling an assessment of the psychometric functions of each list of 27 digits, and allowing the calculation of their L_{mid} and slope values. This data is shown in Table 7, while the generated psychometric functions are shown in Figure 14 and Figure 15.

Table 7. Details of the psychometric functions of the ten test lists.

	Lmid	**Slope at midpoint:**
List 1	-12.9dB	16.5%/dB
List 2	-13.0dB	20.8%/dB
List 3	-12.9dB	18.7%/dB
List 4	-13.0dB	15.9%/dB
List 5	-13.3dB	12.6%/dB
List 6	-13.3dB	23.7%/dB
List 7	-12.6dB	14.5%/dB
List 8	-12.9dB	18.6%/dB
List 9	-12.6dB	20.6%/dB
List 10	-11.9dB	11.0%/dB
Mean:	-12.8dB	17.3%/dB
Std Deviation:	0.4dB	3.9%/dB

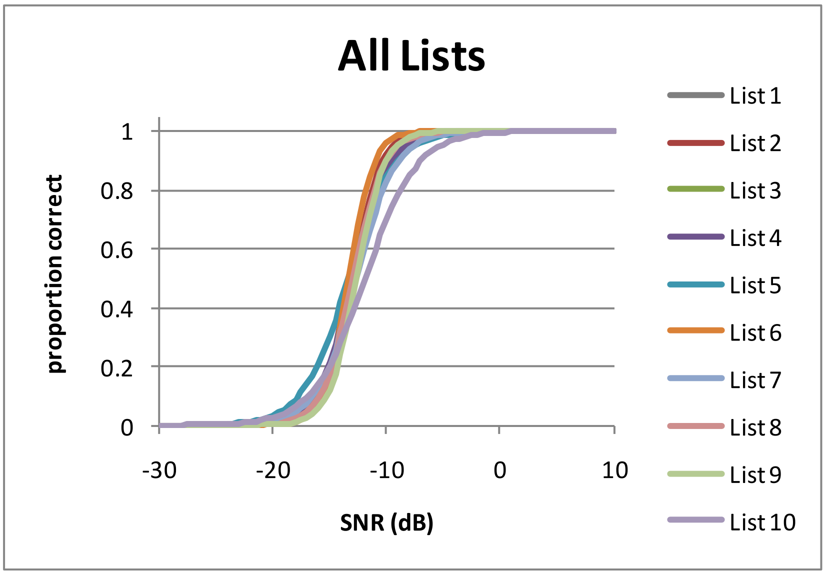

Figure 14.Psychometric functions for each of the DTT test lists.

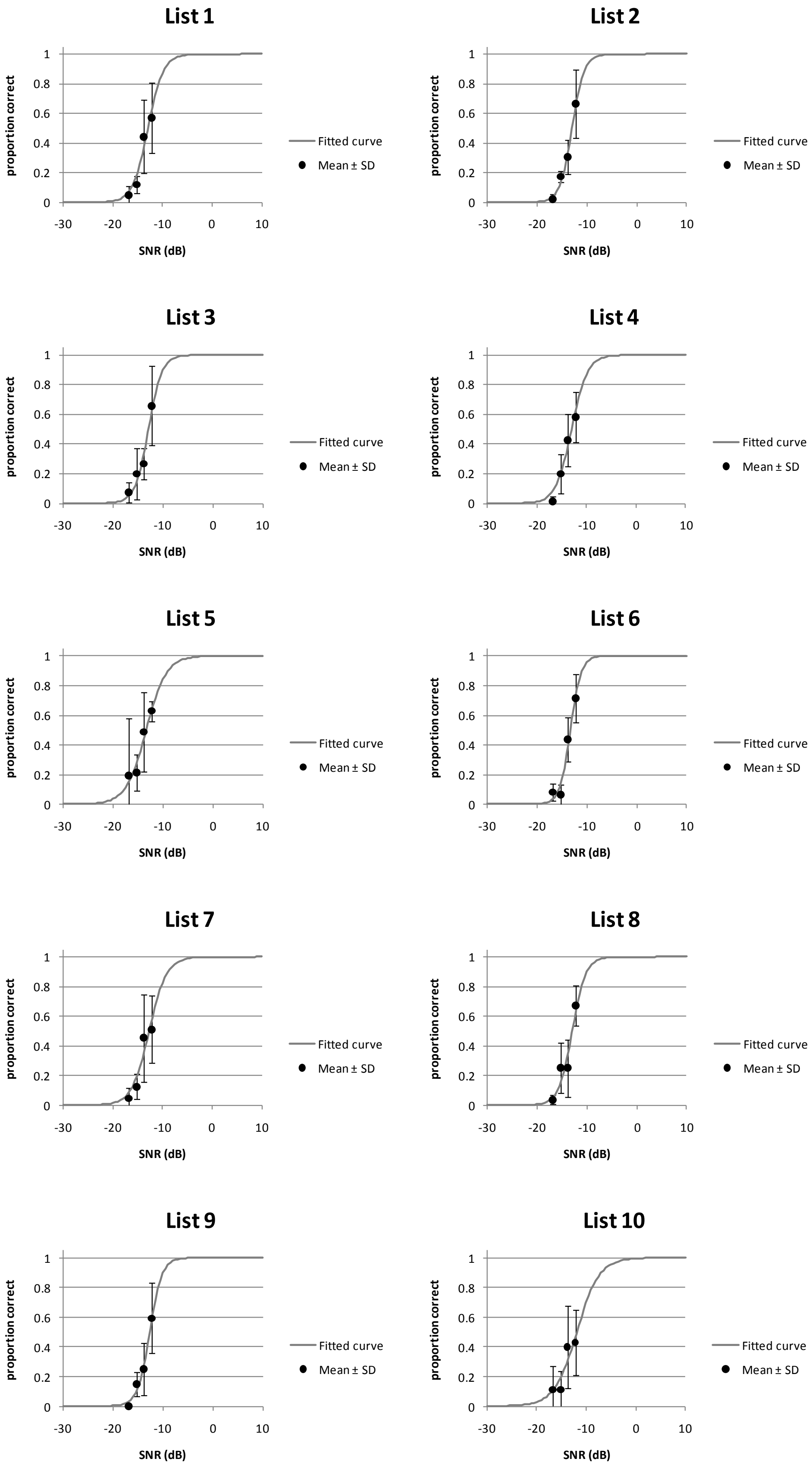

Figure 15. Psychometric function graphs for each DTT test list.

The 10 lists were generated based on the theoretical triplet slope results calculated from the digit slope values produced in the first normalisation process. The calculated triplet slope values were presented in Table 7. Following the second normalisation process, the actual distributions of the triplet slope values for each list were able to be assessed and are shown in Table 8 below:

Table 8. Summary of the distribution of triplet slope values for the ten lists following the second normalisation process, expressed in the same format as Table 7.

	List 1	List 2	List 3	List 4	List 5	List 6	List 7	List 8	List 9	List 10	*Mean*	*Std Dev*	*Max*	*Min*
Average slope	**15.3**	**15.3**	**15.2**	**14.8**	**15.3**	**15.4**	**15.4**	**15.2**	**15.3**	**15.3**	*15.3*	*0.2*	*15.4*	*14.8*
Std Dev	**1.3**	**1.7**	**1.7**	**1.6**	**1.4**	**1.6**	**1.6**	**1.6**	**1.4**	**1.9**	*1.6*	*0.2*	*1.9*	*1.3*
Max slope	**18.6**	**18.1**	**19.2**	**18.1**	**19.2**	**19.2**	**19.2**	**17.8**	**17.8**	**20.0**	*18.7*	*0.8*	*20.0*	*17.8*
Min slope	**13.0**	**12.2**	**12.2**	**12.2**	**13.0**	**11.6**	**12.2**	**11.8**	**12.2**	**11.8**	*12.2*	*0.4*	*13.0*	*11.6*

8 Final Testing Phase: Evaluation of Hearing Screening Test

8.1 Introduction

The final testing phase determined if the NZ DTT was an accurate speech-in-noise test capable of screening a person’s hearing and delivering an appropriate result. This phase of the testing was aimed at establishing the cut-off values that would classify a participant’s results into one of three outcome categories, providing them with a classification of ‘normal’, ‘insufficient’ or ‘poor’ hearing. An appropriate message would then give those persons who receive a ‘normal’ result information about preserving their hearing, and advise someone who receives an ‘insufficient’ or ‘poor’ result to seek further professional advice (HEARCom, 2005; Jansen et al., 2010; Ozimek et al., 2009; Smits et al., 2004). While the test will eventually be made available over a broadband internet connection and over the telephone, only the broadband version of the test was examined in this stage.

8.1.1 Additional Test: QuickSIN Test

When developing the DTT several other research teams validated their DTT test thresholds against a sentence-in-noise test (HEARCom, 2005; Jansen et al., 2010; Ozimek et al., 2009; Smits et al., 2004). As no NZ sentence-in-noise test is currently available, it was decided to use the QuickSIN version 1.3 in this study. This test was included to measure whether there was any correlation between this type of speech-in-noise test and the DTT and PTA for each participant. QuickSIN version 1.3 uses a female talker with four-person-babble as the background noise that is adjusted (made more difficult) sentence by sentence in order to obtain a SRT of 50% correct. The QuickSIN version 1.3 is a sentence test that uses SNRs that are much higher than the NZ DTT. Each QuickSIN test set contains six sentences, with one sentence at each SNR of 25, 20, 15, 10, 5, and 0 dB. The participants listened to 5 sets of lists (Track 24 –Track 28). All participants listened to the 5 QuickSIN lists via a GSI 61 audiometer wearing either TDH-39 headphones or ER -3A insert earphones at the recommended presentation level of 70 dB HL. The QuickSIN test uses key word scoring to determine SNR and provides an estimate of SNR loss accurate to ±2.7 dB at the 95% confidence level (Killion, Niquette, & Gudmundsen, 2004).

8.1.2 Participants

At total of 73 participants were drawn from the University of Canterbury staff and from the community to participate in the final phase of the DTT study. No attempt was made to control for the hearing loss configuration as a wide range of varying hearing loss was required to validate the screening test. After signing a consent form, participants' eardrums were visually inspected using an otoscope to determine ear health. Any participants who had not had a recent audiogram (within the last 6 months) received a diagnostic hearing test – the gold standard test for determining hearing sensitivity. The PTA was the reference standard to which the DTT test results would be compared. A pure-tone audiogram was recorded using a GSI 61 clinical audiometer and either TDH-39 headphones or ER-3A inserts. Immittance measures were made to check for any conductive hearing loss (Type B or Type C tympanograms) that could complicate the DTT results. The data gathered was used to compute the average $PTA_{(.250,\ 0.5,1,2,4,\ 8\ kHz)}$ for each participant. While the term PTA usually refers to the average of only three thresholds, we are using the term $PTA_{(.250,\ 0.5,1,2,4,\ 8\ kHz)}$ to refer to the average of the thresholds at these six frequencies. One participant who had a conductive hearing loss was excluded from the study as was one participant who was unable to complete all three testing conditions, leaving 71 participants from whom DTT results were gathered and analysed.

8.1.3 Method

Participants listened to randomly selected DTT lists using Sennheiser HD 270 pro headphones. The participants listened to three presentations – one delivered binaurally and then one in each ear separately. The order of each ear presentation was randomly assigned during the testing. Some participants listened to a different list for each test condition (Figure 19) while other participants were assigned the same list in all three conditions (Figure 20) as a test/retest measure. The order of the triplets presented in each list was shuffled each time. Participants were instructed to enter their responses via the computer keyboard. A triplet was scored correct only when all three digits were identified correctly. Participants were encouraged to have a guess if they were not sure what they heard. At the conclusion of the test participants were asked to complete a questionnaire (**Appendix II**). The testing was conducted in a single sound-proof booth (the GNResound Booth 2 located in the University of Canterbury's Rutherford Building). After the testing, each participant completed a brief questionnaire about the DTT and hearing tests in general. Approval for the study was obtained from the University of Canterbury Ethics Committee (**Appendix I**).

9 Binaural DTT Results

No binaural sound field PTA testing was conducted as this measure gives the threshold of the 'better ear' rather than a true binaural average threshold. The audiometric testing conducted for the study was based on separate ear thresholds. A total of 71 participants with ages ranging from 19 to 72 years completed the binaural DTT. The participants could be grouped by the average of the thresholds in the better ear at each frequency between 250 Hz to 8 kHz.

Group One consisted of 62 participants (34 females, M = 50 years, SD ± 14 years; PTA M = 9 dB HL, SD ± 5.14 dB HL; DTT threshold M = -12.1 dB SNR, SD ± 1.76 dB; and 28 males, M = 43 years; SD ± 14.5 years; PTA M = 9.30 dB HL, SD ± 5.64 dB HL; DTT threshold M = -12.3 dB SNR, SD ± 2.04 dB). A number of Group One participants had one or two high frequency thresholds slightly > 20 dB HL but when the average of all the thresholds in the better ear for each frequency was calculated the PTA was consistent with the NH classification (≤ 20 dB HL).

Group Two consisted of nine participants (3 female, M = 44 years, SD ± 7 years; PTA M = 24 dB HL, SD ± 0.96 dB; DTT threshold M = -7.4 dB SNR, SD ± 1.41 dB; and 6 male M = 63 years, SD ± 4 years; PTA M = 29.5 dB HL, SD ± 5.8 dB HL; DTT threshold M = -6.4 dB SNR, SD ± 5.8 dB;) with thresholds > 20 dB HL and were classified as having a hearing impairment. It was observed that individuals in Group Two had two or three high frequency thresholds (2 kHz - 8 kHz) > 20 dB HL. The hearing loss was in one or both ears. The high frequency hearing loss component resulted in a PTA > 20 dB HL.

A Pearson product-moment correlation coefficient was computed to assess the relationship between the binaural average of the thresholds in the better ear at each frequency (250 Hz – 8 kHz) and the binaural triplet test SNR threshold (n=71). The two variables were strongly correlated ($r = .816$, $p < 0.001$) as shown in Figure 16.

A receiver operating characteristic (ROC) curve was generated to provide the calculation for the cut-off values to estimate the true positive rate (sensitivity) and false positive rate (1-specificity) for the binaural triplet test (Figure 17). This involved using the DTT threshold, which in this case is the index score compared to the reference standard, which is the person's PTA score. The ROC curve (Figure 17) was used to find the most sensitivity relationship between the DTT threshold and PTA reference score. The binaural triplet test was found to have a sensitivity of 100% and specificity of 85%. The cut-off value for NH is one standard deviation (SD) from the NH mean DTT threshold ($M = -12.20$ dB SNR; $SD = \pm 1.90$ dB) and the cut-off value for HI (poor) is set at two SDs from the NH mean. The 'normal' classification cut-off value was set at -10.30 dB SNR and the 'poor' classification cut-off value was set at -8.40 dB SNR (Figure 18). These values resulted in 20 participants (9 female and 11 male) consisting of both NH and HI receiving an 'insufficient' or 'poor' classification. All nine HI participants (3 female and 6 male; red triangles in Figure 18) were classified correctly as 'poor' by the triplet test. The remaining 11 NH participants' triplet thresholds (green circles in Figure 18) classified them as having 'insufficient' or 'poor' hearing. Examination of the NH participants who were classified as having 'insufficient' or 'poor' hearing on the basis of separate ear thresholds revealed at least a mild high frequency loss in one ear and at worst a moderate high frequency hearing loss for three thresholds in one or both ears (asymmetrical hearing loss) (Figure 18). The averaging of the thresholds in the better ear at each frequency resulted in excellent low frequency thresholds from 250 Hz to 1 kHz (< 15 dB HL), concealing any high frequency hearing loss or asymmetry. Further analysis showed that 15 (75%) participants who 'failed' the binaural DTT screening also 'failed' both separate ear DTT screening tests. The remaining 5 (25%) participants failed at least one separate ear test. The message provided to participants who achieve a DTT threshold that places them in the 'insufficient' or 'poor' category is to have their hearing checked by a professional.

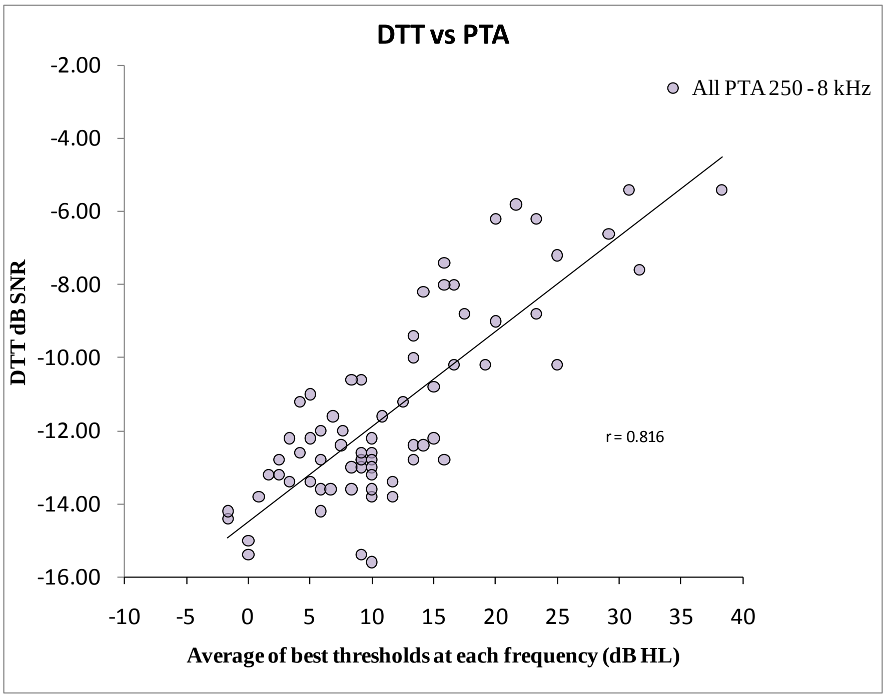

Figure 16. Scatterplot of the binaural triplet test SNR (dB) compared with the binaural average of the thresholds of the better ear at each frequency between 250 Hz to 8 kHz, with the regression line and R value.

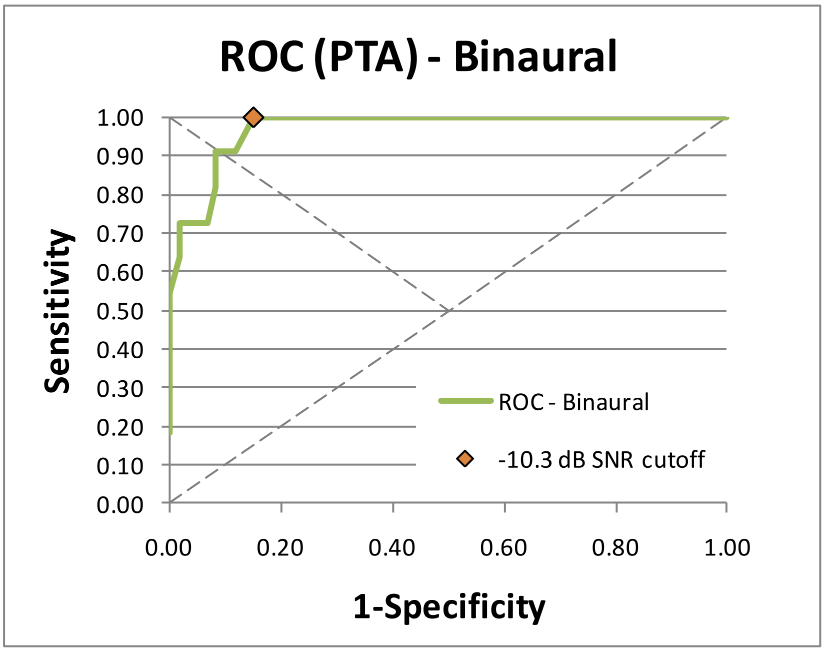

Figure 17. ROC curve for binaural triplet test results.

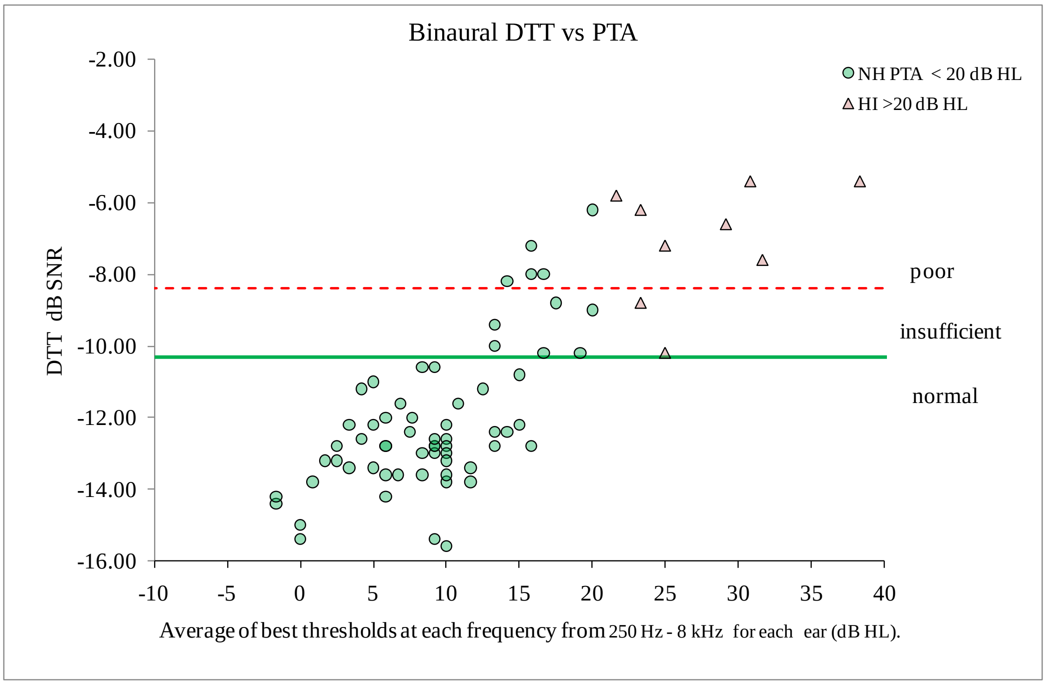

Figure 18. A scatterplot diagram with cut-off values for 'normal' (-10.30 dB SNR) and 'poor' (-8. 40 dB SNR) hearing classification for the binaural triplet test versus the average of best thresholds for the frequencies 250 Hz – 8 kHz for each ear (dB HL). Note: some participants achieved the same threshold so it is possible that a circle or triangle represents two or more participants on the figure; the various tables give the actual count.

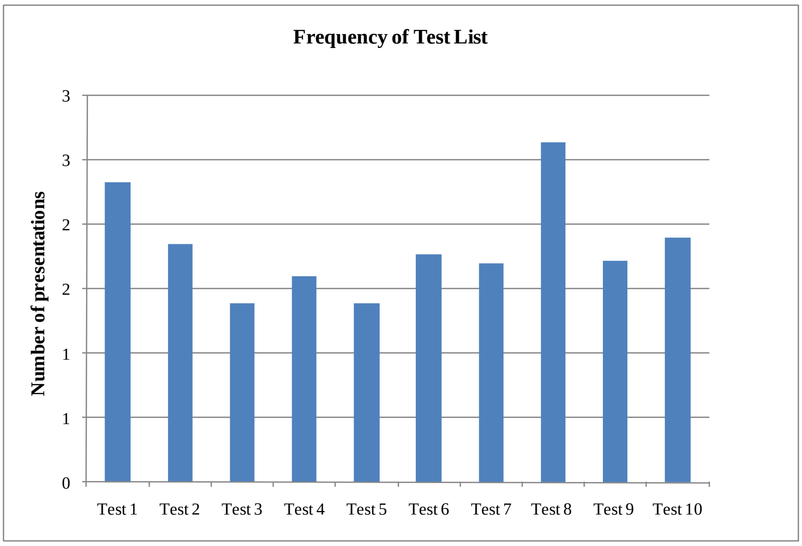

Figure 19. Frequency of test list across all three test conditions

9.1 Same Test List Results

In order to determine if any test-retest variability existed, a number of participants (n = 17; seven female and ten male; average age 49 years; PTA = 17 dB HL) listened to the same list for the three test conditions (binaural, right ear and left ear) (Figure 20). The order of the tests was randomised and administered one after another without informing the participant that they were listening to the same list. The data was analysed to see if any of the thresholds for each test situation improved despite the different listening conditions. For example, Participant One may have been given list 5 first binaurally, then presented this list again to the left ear only and finally to the right ear. This was done for each participant with the order of testing randomised for the 3 test conditions (binaural, right ear and left ear).

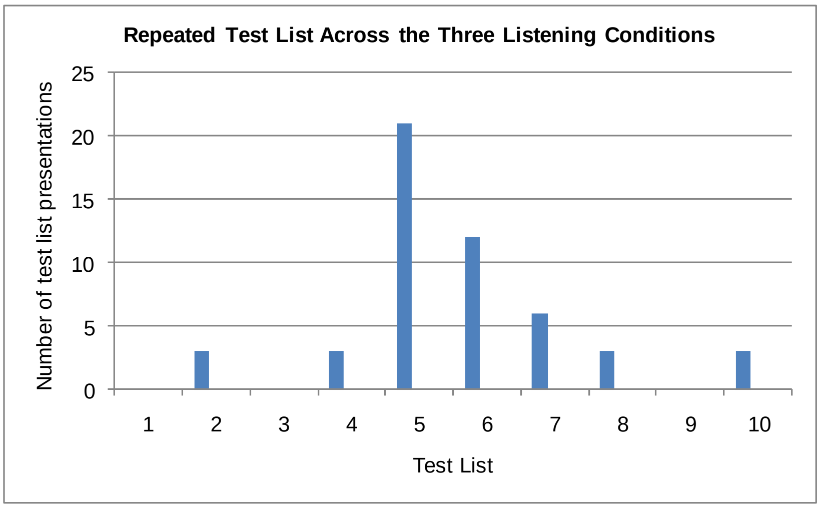

Figure 20. Repeated test lists for the 3 listening conditions (binaural, right ear, and left ear). Test List 5 was the one administered to most re-test participants.

A one-way ANOVA on ranks analysis revealed that there was no significant time order effect within subject factor for the DTT thresholds (χ = 5.262, DF = 2, p = 0.072). This means that no 'learning' occurred and that people could repeat the DTT test a number of times without improving their DTT thresholds.

10 Separate Ear DTT Results

A total of 142 separate ear test results were obtained for the right and left ear (Table 9). NH is defined as the average best threshold in each ear for the frequencies 250 Hz – 8 kHz ≤ 20 dB HL and is represented by green circles in Figure 23. HI is defined as the average threshold in each ear for the frequencies 250 Hz – 8 kHz > 20 dB HL and is represented by the red triangles in Figure 23. Separate ear participant information and results are shown in Table 9.

Table 9. Participant Information

Classification	Number	R Ear	L Ear	Age	PTA (dB HL)	DTT (dB SRT_n)
NH Female	61 (43%)	n = 31	n = 30	M = 49 years SD = 4.83	M = 10.17, SD = 4.83	M = -11.97, SD = 1.69
NH Male	48 (34%)	n = 24	n = 24	M = 41 years SD = 4.77	M = 10.23, SD = 4.77	M =-12.33, SD = 1.84
HI Female	13 (9%)	n = 6	n = 7	M = 50 years SD = 2.46	M = 24.10, SD = 2.46	M =-8.34, SD =1.90
HI Male	20 (14%)	n = 10	n = 10	M = 60.5 years SD = 7.9	M =30.88, SD = 7.9	M =-6.06, SD = 2.75
Total	142 (100%)	n = 71	n = 71	M = 48 years SD = 14.59	M= 14.38, SD = 9.34	M = -10.98, SD = 2.97

A Pearson product-moment correlation coefficient was computed to assess the relationship between the separate ear PTA and the separate ear triplet test threshold (n = 142). The two variables were strongly correlated ($r = .809$, $p < 0.001$) (Figure 21).

Separate ear ROC curves were generated to provide the cut-off values for the separate ear triplet test (Figure 22). The cut-off value for NH is one standard deviation (SD) from the NH DTT threshold (M = -12.15 dB SNR; SD ± 1.75 dB) which results in a cut-off value of -10.40 dB SNR. The cut-off value for HI (poor hearing) is two SD's from the NH mean which means that the 'poor' classification cut-off value is set at -8.65 dB SNR (M = 6.96 dB SNR;

SD ± 2.67 dB) (Figure 23). The ROC shows that the chosen cut-off value of -10.40 dB SNR yields a sensitivity of 88% and specificity of 81% as shown in Figure 22.

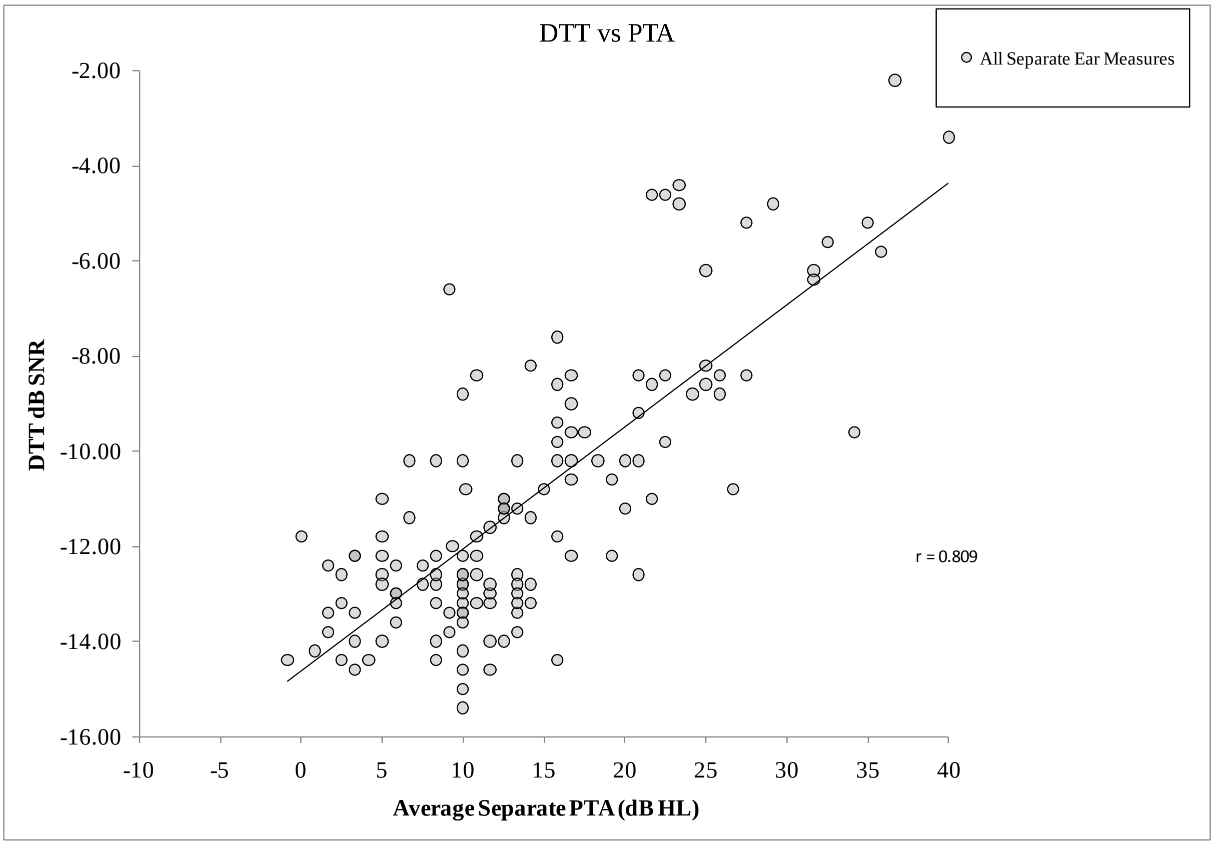

Figure 21. Scatterplot and linear regression for separate ear triplet test and separate ear average thresholds from 250 Hz to 8 kHz (dB HL) with regression line and R value.

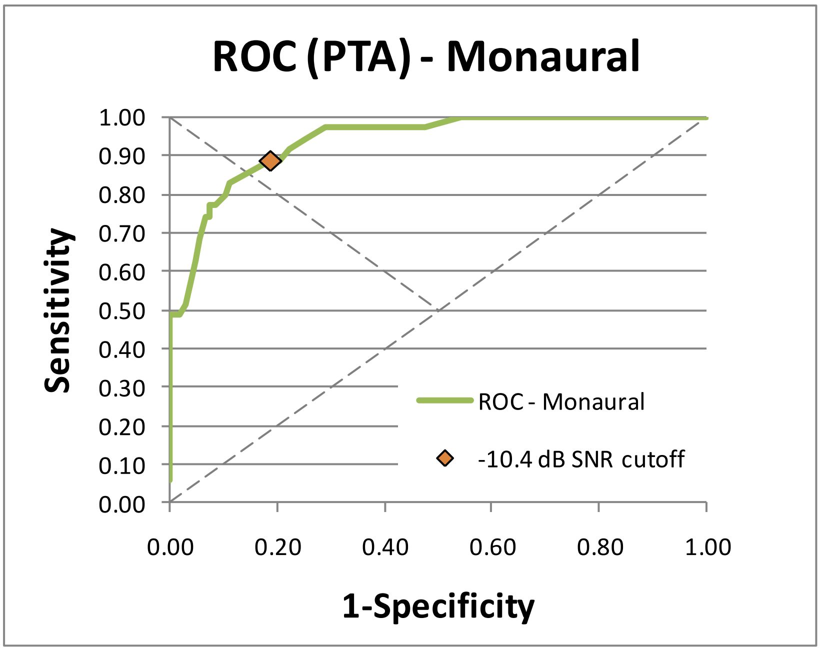

Figure 22. ROC curve for separate ear triplet test.

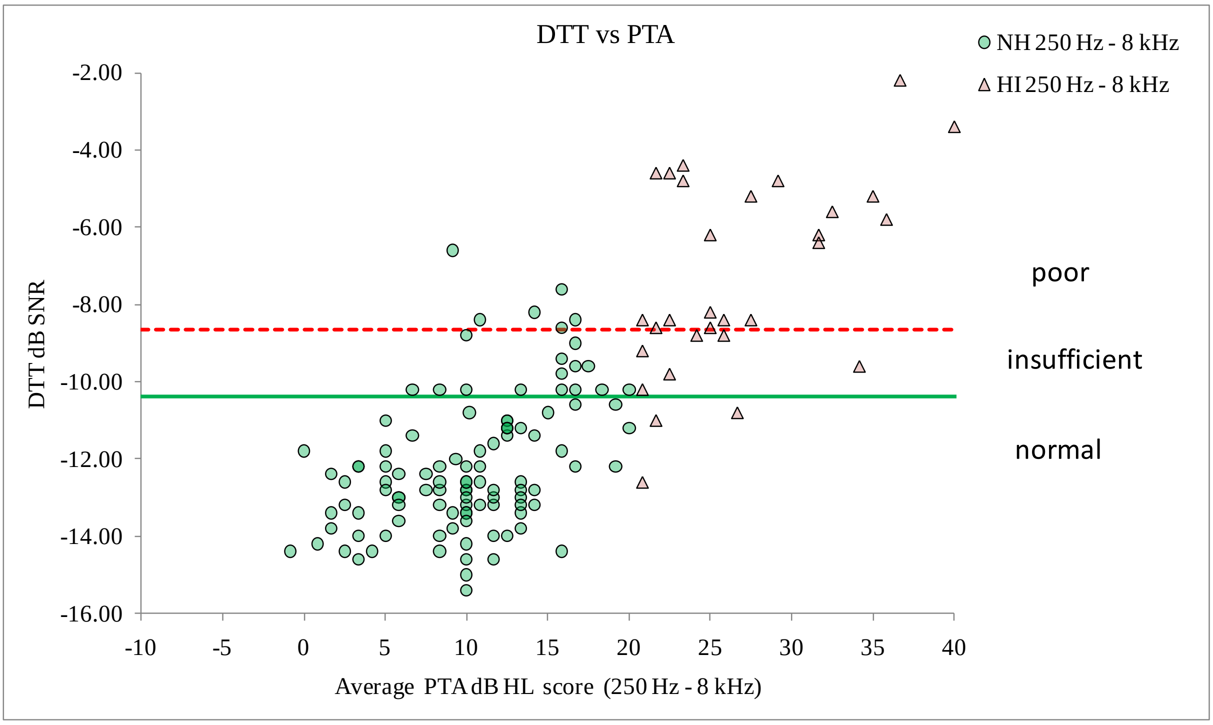

Figure 23. Scatterplot with cut-off values for 'normal' hearing (-10.40 dB SNR) and 'poor' hearing (-8.65 dB SNR) for the separate ear triplet thresholds compared to the separate ear PTA for the average thresholds from 250 Hz to 8 kHz (dB HL). Note: some participants achieved the same threshold so it is possible that a circle or triangle represents two or more participants on the figure; the various tables give the actual count.

An analysis of NH participants whose separate ear DTT threshold (green circles, Figure 23) fell into the ‘insufficient’ or ‘poor’ hearing classification is shown in Table 10. A review of individual thresholds for these NH participants who were classified by the DTT as having ‘insufficient’ hearing revealed 4 participants with possible age-related cognitive issues (they were each over 69 years old) or possibly an undiagnosed auditory processing disorder. It was not possible to ascertain from the screening test the reason for this result, as further testing would be required which was outside the scope of this study. The remaining 17 NH participants who received an ‘insufficient’ or ‘poor’ result were further analysed. Their audiograms showed they all had a mild to moderate high frequency loss at 8 kHz and /or 4 kHz with excellent low frequency hearing for thresholds from 250 Hz – 2 kHz < 20 dB HL. The excellent low frequency measures meant these people were classified as NH when the PTA was calculated. Referring this group of NH participants to seek a diagnostic hearing test would be beneficial.

Table 10. Analysis of the separate ear DTT thresholds below -10.40 dB SNR and an average NH PTA ≤ 20 dB HL (green circles) who were placed in the ‘insufficient’ and ‘poor’ classification sections of Figure 23.

Classification	Number	Age	R Ear	L Ear	PTA (dB HL)	DTT (dB SNR)	DTT Rating
NH Female	n = 14	M=58 years, SD = 16.92	n = 5	n = 9	M = 13.10, SD 3.72	M = -9.49, SD 0.83	Insufficient
NH Male	n = 7	M = 59 years, SD = 10.21	n = 3	n = 4	M = 15.83, SD = 3.30	M = -9.00, SD = 1.39	Insufficient
Total	n = 21	M = 58.5 years, SD = 14.75	n = 8	n = 13	M=14.01, SD = 3.74	M = -9.32, SD = 1.04	Insufficient

Three HI participants who had an average PTA > 20 dB HL (red triangles in the normal range, Figure 23) received a classification of ‘normal’ hearing and did not receive advice to seek further diagnostic testing. Further examination of their audiogram thresholds revealed only a mild high frequency loss (25 dB HL at 8 kHz). This would explain why these individuals were able to pass the DTT as their average PTA was between 20 to 25 dB HL. Details for these three HI participants are shown in Table 11.

Table 11. Hearing impaired participants with separate ear average PTA > 20 dB HL (red triangles) whose separate ear DTT threshold placed them in the ‘normal’ classification area of Figure 23.

HI - Sex/Number		Age	R Ear	L Ear	PTA (dB HL)	DTT (dB SNR)	DTT Rating
Female (2) Male (1)	n = 3	M = 62 years, SD = 6.25	n = 1	n = 2	M=23.06, SD = 3.15	M = -11.47, SD = 0.99	Normal

The participants (n = 30) whose triplet threshold above– 10.40 (dB SNR) placed them in the ‘insufficient’ or ‘poor’ category had an average PTA > 20 dB HL. The red triangles in the ‘insufficient’ and/or ‘poor’ sections of the graph (Figure 23) represent this group of participants. Of this group 24 separate ear results represent 12 individuals who failed both separate ear tests. Twenty-nine participants in this group also failed the binaural triplet test. This group of participants regardless of the testing condition received consistent feedback that they had a hearing impairment and should seek further professional advice regarding their hearing (Figure 23 and Table 12).

Table 12. Separate ear participant information for those who had an average PTA > 20 dB HL (red triangles) and a triplet threshold above - 10.40 (dB SNR) and received an 'insufficient' or 'poor' rating. (Note: excludes the 3 red triangles in the ‘normal’ classification region of Figure 23; see Table 11 for information on these participants).

Classification	Number	Age	R Ear	L Ear	PTA (dB HL)	DTT (dB SNR)	DTT Rating
HI Female	n = 11	M = 48 years, SD = 9.67	n = 5	n = 6	M = 24.09, SD = 2.46	M = -7.87, SD = 1.67	Insufficient/Poor
HI Male	n = 18	M = 61 years, SD = 6.53	n = 10	n = 9	M = 31.40, SD = 7.74	M = -5.72, SD = 2.35	Insufficient/Poor
Total	n = 30	M = 56 years, SD = 9.77	n = 15	n = 15	M = 28.72, SD = 7.22	M = -6.51, SD = 2.35	Insufficient/Poor

The NH participants (n=88) with an average PTA ≤ 20 dB HL are shown with separate DTT results with thresholds lower than -10.40 dB SNR (green circles in normal classification section of Figure 23. Details about age, separate ear number, PTA and DTT results are in Table 13).

Table 13. Normal hearing participants who have an separate ear average PTA < 20 dB HL and a separate ear DTT threshold greater than -10.40 dB SNR (green circles) whose DTT threshold placed them in the 'normal' classification area of Figure 23.

Classification	Number	Age	R Ear	L Ear	PTA (dB HL)	DTT (dB SNR)	DTT Rating
NH Female	n = 47	M=47 years, SD = 12.90	n = 26	n = 21	M = -12.71, SD = 1.05	M = -9.29, SD = 4.82	Normal
NH Male	n = 41	M = 38 years, SD = 12.78	n = 21	n = 20	M = 12.90, SD = 1.20	M = -9.27, SD = 4.32	Normal
Total	n = 88	M = 43 years, SD = 13.47	n = 47	n = 41	M = 9.28, SD = 4.56	M = -9.32, SD = 1.04	Normal

10.1 Correlation of Age and Sex to PTA and DTT Results

The results for all separate ear measurements have also been grouped into age ranges for the purpose of examining any relationships between age, gender, DTT threshold and mean PTA score for the participants (

Table 14). The results include both NH and HI participants.

A Pearson product-moment correlation coefficient was computed to assess the relationships between age, the separate ear mean PTA and the mean separate ear triplet test threshold for all participants. In order to include gender (a nominal variable) in the analysis the results for both male and females were combined ($n = 142$) and it was found that the PTA is highly correlated with the DTT threshold and mildly correlated with age (Table 15).

Similar correlations between PTA and the DTT threshold were found in the correlation analysis for female participants ($n=74$, $r = 0.719$, $p <0.001$) and male participants ($n =68$, $r = 0.840$, $p <0.001$). However, there appears to be a gender difference in relationships between age and both PTA and DTT thresholds. Specifically, for females ($n=74$) age is not correlated with mean PTA ($r = 0.268$, $p = 0.0212$), or DTT thresholds ($r = 0.32$, $p = 0.00549$). In contrast, for males ($n = 68$) age is significantly and positively correlated with mean PTA ($r = 0.655$, $p <0.001$) and DTT thresholds ($r = 0.731$, $P < 0.001$).

Table 14. Separate ear results are set out in age groups with gender, average PTA measures and average DTT thresholds including standard deviations.

Age Range	Female	Male	Total	PTA (dB HL) / STDEV	DTT Score (SRTn) / STDeV
19 - 29 years	n= 10	n = 14	n = 24	6.92 dB HL / ± 4.67	-13.25 SRT / ± 1.6
30-40 years	n = 4	n= 12	n = 16	6.44 dB HL / ± 9.56	-12.5SRT / ± 0.35
41-50 years	n = 22	n = 12	n = 34	10.60 dB HL / ± 7.13	-11.06 SRT / ± 2.82
51 - 61 years	n = 22	n = 18	n = 40	15 dB HL / ± 7.45	-10.28 SRT / ± 2.80
62 - 72 years	n = 16	n = 12	n = 28	15.7 dB HL / ± 11.40	-8.81 SRT / ± 3.08

Table 15. Correlation between DTT, PTA and Age for all participants

All participants	Separate Ear PTA Mean (250 Hz – 8 kHz) dB HL	Separate Ear DTT Threshold
Age	r = 0.470 p < 0.001 n = 142	r = 0.545 p < 0.001 n = 142
Separate Ear DTT Threshold	r = 0.809 p < 0.001 n = 142	

10.2 QuickSIN Test Results

A total of 71 participants (37 females and 34 males) listened to the five QuickSIN lists that contained six sentences with varying SNRs. Two participants for whom English was a second language commented that they had difficulty with the language and accent. Their test results were extremely poor compared to others with similar age and hearing PTA, so their test results were excluded from the calculations leaving 69 participant results for analysis.

The spread of scores for the test ranged from 0.0 dB SNR to a high of 9.50 dB SNR. QuickSIN rates participants with QuickSIN scores between 0 – 3 dB SNR as having normal/near normal hearing. Results for this group are as follows: n=51; mean age = 49 years, SD ± 13.63; average PTA 12.3 dB HL, SD ± 2.04; mean QuickSIN score = 1.14 SNR, SD ± 0.88.

QuickSIN rates participants with scores between 3 – 15 dB SNR as having a mild to moderate SNR hearing loss. Results for this group are as follows: n = 12; mean age =61.5 years, SD ± 10.5; average PTA 21.3 dB HL, SD ± 8.36; mean QuickSIN score = 4.55 SNR, SD ± 1.78.

A Pearson product-moment correlation coefficient was computed to assess the relationship between the binaural PTA average of the thresholds in the better ear at each frequency (250 Hz – 8 kHz), the binaural DTT threshold and the QuickSIN score. A significant relationship was found between the various conditions as shown in Table 16.

Table 16. Person Product Moment Correlation Results for QuickSIN score; Mean PTA dB HL and DTT Threshold.

	QuickSIN Score	Binaural PTA Mean (250 Hz – 8 kHz) dB HL
Binaural DTT Threshold	$r = 0.668$ $p < 0.001$ $n = 69$	$r = 0.816$ $p < 0.001$ $n = 69$
Binaural PTA Mean (250 Hz – 8 kHz) dB HL	$r = 0.570$ $p < 0.001$ $n = 69$	

10.3 Questionnaire Results

The questionnaire (Appendix II) given to participants was designed to examine the attitudes of the participants to the hearing screening test (Figure 24). All 73 participants completed the questionnaire and responded in the affirmative (100%; Question 1) that a hearing screening test like the DTT would be a valuable public health service. If the screening test advice was to have a diagnostic hearing testing, 90% responded 'Yes' that they would seek further professional advice (Question 2). A detailed analysis of the questionnaire results follows:

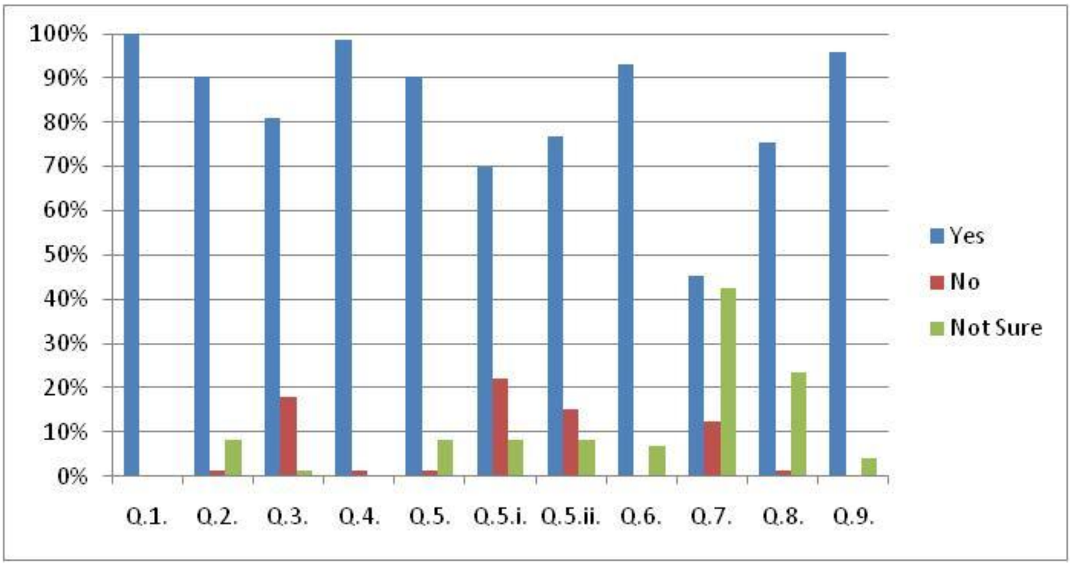

Figure 24. Questionnaire results

11 Responses to the Questionnaire

The following details the responses of the participants as a complete group to each question. The analysis categorises the responses by sex and age group (age group 19-35 - female n = 6, male n = 9; age group 36-52, female n = 14, male n = 10; age group 53-62^{+} - female n = 19, male n = 15).

Question 1. – 'Do you think that a hearing screening test like the Digit Triplet Test you took today would be a valuable service?'

Group Analysis

Total N = 73		
Yes n =	73	100%
No n =	0	0%
Unsure n =	0	0%
Total		100%

Responses by Sex and Age Group

	19-35	(%)	36-52	(%)	53-69+	(%)
Female						
Yes	6	100%	14	100%	19	100%
No	0		0		0	
Unsure	0		0		0	
Male						
Yes	9	100%	10	100%	15	100%
No	0		0		0	
Unsure	0		0		0	
Total Responses	73					

Question 2. – 'If the Digit Triplet screening test told you that you might have a hearing loss, would you seek a more detailed hearing test from a professional to find out more?'

Group Analysis

Total N = 73		
Yes n =	66	90%
No n =	1	1%
Unsure n =	6	8%
Total		100%

Responses by Sex and Age Group

	19-35	(%)	36-52	(%)	53-69+	(%)
Female						
Yes	6	100%	12	86%	17	89%
No	0		1	7%	0	
Unsure	0		1	7%	2	11%
Male						
Yes	9	100%	10	100%	12	80%
No	0		0		0	
Unsure	0		0		3	21%
Total Responses	73					

Question 3. – 'Would you use a hearing screening test such as the Digit Triplet Test if it was available over the telephone? (The test would provide you with results and a brief explanation and recommendation).'

Group Analysis

Total N = 73		
Yes n =	63	86%
No n =	9	12%
Unsure n =	1	1%
Total		100%

Responses by Sex and Age Group

	19-35	(%)	36-52	(%)	53-69+	(%)
Female						
Yes	6	100%	11	79%	15	79%
No	0		3	21%	3	16%
Unsure	0		0		1	5%
Male						
Yes	8	89%	9	90%	14	93%
No	1	11%	1	10%	1	7%
Unsure	0		0		0	

Total Response 73

Question 4. – 'Do you have internet service at home?'

Group Analysis

Total N = 73		
Yes n =	72	99%
No n =	1	1%
Total		100%

Responses by Sex and Age Group

	19-35	(%)	36-52	(%)	53-69+	(%)
Female						
Yes	6	100%	14	100%	18	95%
No	0		0		1	5%
Unsure	0		0		0	
Male						
Yes	9	100%	10	100%	15	100%
No	0		0		0	
Unsure	0		0		0	

Total Responses 73

Question 5. -'Would you use a hearing screening test such as the Digit Triplet Test if it was available on the internet? (The test would provide you with results and a brief explanation and recommendation).'

Group Analysis

Total N = 73		
Yes n =	66	90%
No n =	1	1%
Unsure n =	6	8%
Total		100%

Responses by Sex and Age Group

	19-35	(%)	36-52	(%)	53-69+	(%)
Female						
Yes	6	100%	12	86%	15	79%
No	0		0		1	5%
Unsure	0		2	14%	3	16%
Male						
Yes	9	100%	9	90%	15	100%
No	0		0		0	
Unsure	0		1	10%	0	

Total Responses 73

Question 5i. – 'Does your home computer have external speakers that you could use to listen to a hearing screening test available on the internet?'

Group Analysis

Total N = 73		
Yes n =	51	70%
No n =	16	22%
Unsure n =	6	8%
Total		100%

Responses by Sex and Age Group

	19-35	(%)	36-52	(%)	53-69+	(%)
Female						
Yes	6	100%	10	71%	10	53%
No	0		3	21%	6	32%
Unsure	0		1	7%	3	16%
Male						
Yes	8	89%	7	70%	10	67%
No	1	11%	3	30%	3	20%
Unsure	0		0		2	13%

Total Responses 73

Question 5ii. – 'Do you have headphones that you could use with the computer to listen to a hearing screening test available on the internet?'

Group Analysis

Total N = 73		
Yes n =	56	77%
No n =	11	15%
Unsure n =	6	8%
Total		100%

Responses by Sex and Age Group

	19-35	(%)	36-52	(%)	53-69+	(%)
Female						
Yes	6	100%	10	71%	11	58%
No	0		4	29%	5	26%
Unsure	0		0		3	16%
Male						
Yes	9	100%	8	80%	12	80%
No	0		2	20%	0	
Unsure	0		0		3	20%

Total Responses 73

Question 6. – 'Do you trust that the result of the Digit Triplet hearing screening test you have taken today is accurate?'

Group Analysis

Total N = 73		
Yes n =	68	93%
No n =	0	0%
Unsure n =	5	7%
Total		100%

Responses by Sex and Age Group

	19-35	(%)	36-52	(%)	53-69+	(%)
Female						
Yes	4	67%	14	100%	18	100%
No	0		0		0	
Unsure	2	33%	0		1	
Male						
Yes	8	100%	9	90%	15	100%
No	0		0		0	
Unsure	1		1	10%	0	

Total Responses 73

Question 7. – 'Would you trust a **telephone** Digit Triplet hearing screening test which provided you with results and an explanation?'

Group Analysis

Total N = 73		
Yes n =	34	47%
No n =	9	12%
Unsure n =	30	41%
Total		100%

Responses by Sex and Age Group

	19-35	(%)	36-52	(%)	53-69+	(%)
Female						
Yes	4	67%	6	43%	9	47%
No	0		2	14%	2	11%
Unsure	2	33%	6	43%	8	42%
Male						
Yes	6	67%	1	10%	8	53%
No	1	11%	3	30%	1	7%
Unsure	2	22%	6	60%	6	40%

Total Responses 73

Question 8. – 'Would you trust **an internet** Digit Triplet hearing screening test that provided results and an explanation?'

Group Analysis

Total N = 73		
Yes n =	56	77%
No n =	1	1%
Unsure n =	16	22%
Total		100%

Responses by Sex and Age Group

	19-35	(%)	36-52	(%)	53-69+	(%)
Female						
Yes	5	83%	11	79%	12	63%
No	0		0		0	
Unsure	1	17%	3	21%	7	37%
Male						
Yes	7	78%	7	70%	13	87%
No	0		1	10%	0	
Unsure	2	22%	2	20%	2	15%

Total Responses 73

Question 9. – 'Would you recommend a hearing screening like the Digit Triplet Test to other people?'

Group Analysis

Total N = 73		
Yes n =	70	96%
No n =	0	0%
Unsure n =	3	4%
Total		100%

Responses by Sex and Age Group

	19-35	(%)	36-52	(%)	53-69+	(%)
Female						
Yes	6	100%	14	100%	18	95%
No	0		0		0	
Unsure	0		0		1	5%
Male						
Yes	9	100%	8	80%	15	100%
No	0		0		0	
Unsure	0		2	20%	0	

Total Responses 73

Question 10. -'Which ear do you use to listen to people when talking on the telephone?' (Please circle one answer)' Right Ear Left Ear

Group Analysis

Total N = 73		
Right Ear	52	71%
Left Ear	21	29%
Total		100%

Right and Left Ear by Sex and Age Group

	19-35	(%)	36-52	(%)	53-69+	(%)
Female						
Right Ear	5	83%	9	64%	16	84%
Left Ear	1	17%	5	36%	3	16%
Male						
Right Ear	8	89%	6	60%	8	53%
Left Ear	1	11%	4	40%	7	47%

12 Discussion

12.1 Test Material Development

Smits & Houtgast (2006) identify that the accuracy of the SRT_n in the digit screening test was dependent on a number of factors. First, the intelligibility of the speech material is influenced by participants' guess rates and any lapse in concentration during the testing. Secondly, the characteristics of the test such as the adaptive step size and presentation level of the stimuli and the number of presentations can affect the accuracy of the test. The measurement procedures used to arrive at the 50% intelligibility factor could also be subject to bias. A number of these issues were addressed in the design and testing of the NZ digit triplet test.

The first normalisation process was aimed at checking the psychometric function of individual digits which resulted in adjustments being made that were designed to improve the slope function of each digit. The second aim of the normalisation process was to check that the corrections made to the digits actually resulted in improved slope measurements for each digit so that the triplet combinations of these digits would achieve the highest slope possible for each presentation and combination. Digit four had the shallowest slope for position one and position two (9.73%/dB and 9.40%/dB respectively) (Figure 12) and this issue was not easily resolved. Multiple recordings for each digit could have been included in the first normalisation process, which would have enabled the selection process to have been done using participants. However, the weighting process used in the generation of the ten test lists ensured that the effects of the shallow slope functions for the digit 4 were minimised by reducing the number of occurrences of that digit to only 4% of the total digits presented (as opposed to the digit 8, which had the steeper slope, and comprised 21% of the digits presented).

The NZ triplet test was based on a 2 dB adaptive step size and a 65 dBA presentation level and involved 27 stimuli presentations. The length of the final DTT was approximately 3 minutes 30 seconds. Ensuring the DTT is short in length helps to avoid concentration lapses in test participants. These parameters have been used in a number of other successful international tests (Table 2).

The NZ triplet test used a continuous background noise created from speech stimuli. Other studies have noted that interrupted noise is more effective in separating NH from HI and have trialled the use of different types of noise (McArdle, Wilson, & Burks, 2005; Smits & Houtgast, 2007; Wagener & Brand, 2005; R. Wilson, Burks, & Weakley, 2006; R. Wilson & Weakley, 2004). Smits & Houtgast (2007) investigated a number of differing background stimuli for the telephone triplet test they developed. They reported that fluctuating (modulated or interrupted) noise affected HI participants more than NH participants and resulted in a wider separation in SRT_n for each group. The HI participant performance was worse when interrupted noise was used. Research into audibility factors has found that the poorer performance by the HI can be attributed only in part to poorer audibility and that the more important factor in the decline in performance is a person's degree of sensorineural hearing loss (Bacon, Opie, & Montoya, 1998). The masking release that occurs in fluctuating background noise requires the listener to resolve the temporal pattern of the speech stimuli. It has been found that only normal hearing listeners are able to extract the speech information when the background noise is fluctuating and therefore achieve a high SNR (Bacon et al., 1998; Smits & Houtgast, 2007). Bacon (1998) found that the masking release for HI participants was least when listening to stimuli with a square-wave background modulated noise (10 Hz square wave). The correlation between this masking release condition and the PTA from 200 to 4000 Hz was -0.763. Bacon (1998) attributed this result to sensorineural hearing loss.

Future refinement of the NZ DTT should examine modulated background noise and determine the modulation that works best. Smits & Houtgast (2007) report that the spread of SRT_n among participants with NH and HI was greatest for 16-Hz interrupted noise, followed by 32 Hz interrupted noise. The lowest spread was for continuous noise. For a telephone digit test, Smits & Houtgast (2007) recommend that a 16-Hz interrupted noise be used to screen hearing ability. In 2007, the National Acoustic Laboratories, a division of Australian Hearing, developed Telscreen II, a telephone screening test that presented digits in a background noise that is both spectrally and temporally modified. The background noise has a fixed long-term root mean square level against which digits are presented with variable intensity (Golding, Seymour, Dillon, Carter, & Zhou, 2007). Golding et al.(2007) based their testing on a PTA consisting of the four frequency thresholds from 500 Hz – 4 kHz. This PTA measure was then compared to the Telscreen test threshold (SRT_n). Their linear analysis showed a significant relationship between the PTA and triplet threshold ($r^2 = 0.63$, $n = 109$, $p < 0.001$). The Australian test result is comparable to the NZ DTT result ($r^2 = 0.653$, $n = 143$, $p < 0.001$) which used a continuous background noise (Golding et al., 2007). While the NZ result was achieved with continuous noise it could be beneficial to develop a similar interrupted noise pattern for the NZ DTT broadband version and undertake a comparative study.

12.2 Defining PTA

The development of the DTT was also based around specific criteria used to define a person's PTA. The comparison of PTA to SNR establishes the cut-off value used to separate NH from HI participants. Each of the current digit triplet tests available uses a range of cut-off criteria which best fits the data gathered during testing (Smits & Houtgast, 2007). The sensitivity and specificity of the triplet test depends on the value of the SRT_n, which is used to distinguish between NH and HI participants. The question this raises is: How important is the method used to define a participants PTA? Will different measurements of PTA affect the calculation of the cut-off values used to separate NH from HI participants? Normal hearing is generally defined as audiometric threshold results that fall in the range of -10 dB to 20 dB across the frequencies of 250 Hz – 8 kHz (Schlaunch & Nelson, 2009). For speech intelligibility, emphasis is generally placed on the PTA 500 Hz - 4hKz ≤ 20 dB but clinically, variations in calculating the PTA exist depending on the hearing loss configuration (ASHA, 1988; Schlaunch & Nelson, 2009). Examination of the NZ triplet data showed that defining normal hearing as the best threshold for the frequencies 250 Hz – 8 kHz ≤ 20 dB HL was very similar to using only the best threshold for the frequencies 500 Hz – 4 kHz ≤ 20 dB HL.

Smits et al. (2004) and Wagener (2006) determined that a PTA criterion of 500 Hz – 4 kHz ≤ 20 dB resulted in high sensitivity and specificity for their hearing screening tests. The NZ triplet study used the *best average* threshold for each ear across the frequencies. The difference between using the whole range of frequencies or restricting the analysis to just a few thresholds made little difference to the regression calculation, as the threshold for the frequencies 500 Hz – 4 kHz ($r^2 = 0.6540$) compared to the best thresholds for frequencies 250 Hz – 8 kHz ($r^2 = 0.6539$) was not significantly different. Either PTA frequency measurement established a significant relationship to the DTT.

Siegenthaler and Strand (1964) researched a number of variations in calculating the relationship between PTA and SRT_n. They concluded that different auditory factors influence each PTA measurement and that there is no single method for precisely relating audiogram thresholds to SRT_n. Siegenthaler and Strand (1964) concluded that a two frequency average was the preferred method for relating PTA to SRT_n.

The cut-off values using the 2 frequency PTA model suggested by Siegenthaler and Strand are as follows: ‘normal’ hearing (-9.40 dB SNR) and ‘poor’ hearing (-7.16 dB SNR) (Figure 25). When this was applied to the DTT data the relationship to the PTA decreased ($r^2 = 0.442$) so in fact for this particular speech-in-noise screening test the PTA relationship is dependent on more frequencies, not fewer (Figure 26). For the NZ DTT, the average best threshold for frequencies 250 Hz – 8 kHz was found to be the most sensitive measure of hearing loss.

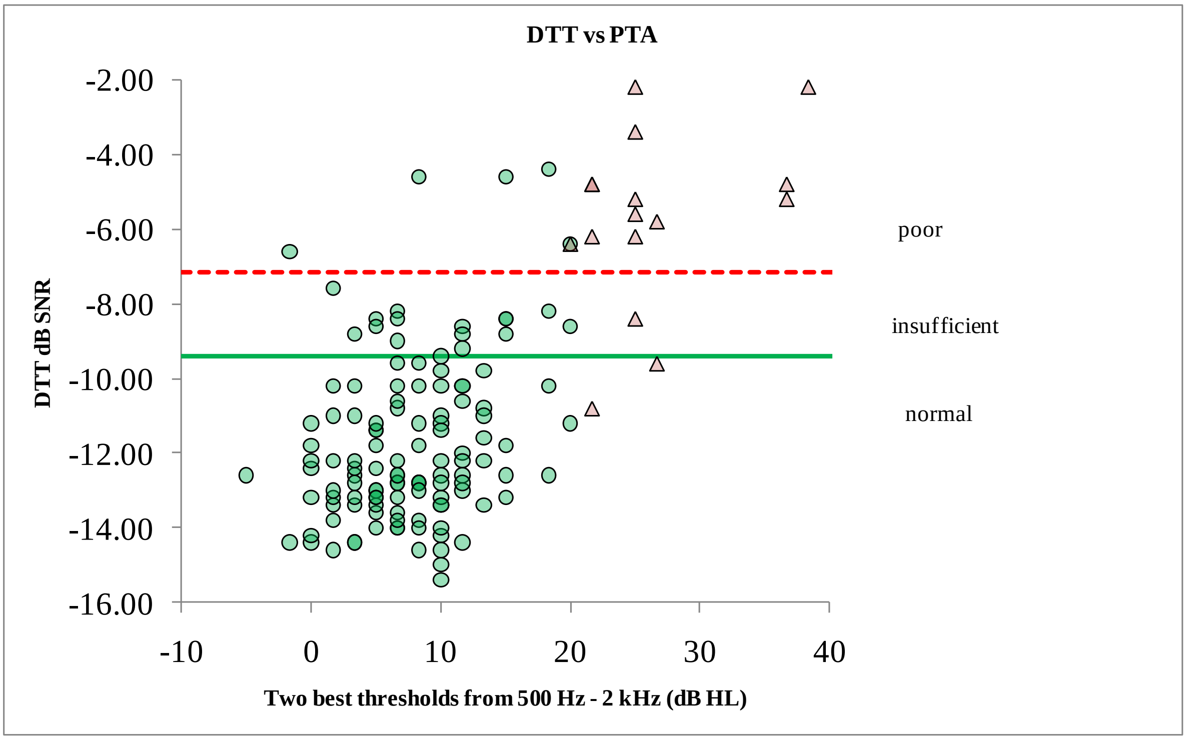

Figure 25. The best two thresholds from 500 Hz - 2 kHz compared to separate ear DTT dB SNR with new cut-off values for ‘normal’ hearing at (-9.40 dB SNR) and ‘poor’ hearing at (-7.16 dB SNR).

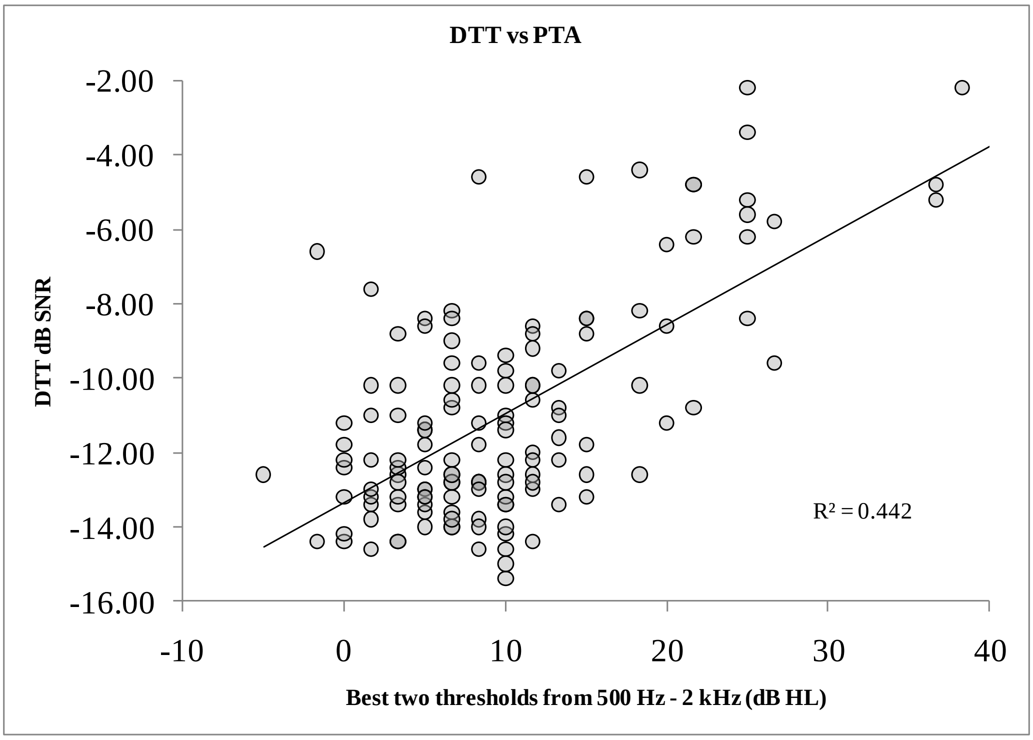

Figure 26. The best two thresholds from 500 Hz - 2 kHz compared to separate ear DTT dB SNR including the regression line and R^2 value.

12.3 Binaural Results versus Separate Ear Results

Participants with averaged best ear threshold measures that concealed a mild high frequency loss which typically involved a loss at 4 kHz and/or 8 kHz did not pass the binaural or separate ear DTT. Despite having excellent low frequency thresholds, with an audiogram that an audiologist would describe as 'essentially' normal hearing, these participants 'failed' all three DTT test conditions. Killion & Niquette (2000) report that the predictive power of the audiogram is very poor and that, despite the numerous methods they used to calculate the PTA, even taking into account audibility and missing hair cells, the predicted 50% SRT_n values in noise (SNR) were out by as much as 15 dB to 20 dB. They concluded that the only reliable way to predict a person's listening performance in noise was to measure it.

The DTT showed that for a number of participants with normal hearing thresholds (≤ 20 dB HL) the audiogram could not predict how they would perform on the DTT. Thirteen participants (female = 10, male = 3) aged 60 and older with normal hearing (PTA ≤ 20 dB 250 – 8 kHz) scored in the 'insufficient' and 'poor' range for the separate ear DTT. Seven other participants over the age of 60 (female = 6, male = 1) with a PTA ≤20 dB HL passed the separate ear DTT.

Why is there a mixed result for this age group with ‘normal’ hearing? Research has shown that older listeners even with normal hearing thresholds consistently perform worse in noise than younger listeners with equivalent thresholds (Dubno et al., 1984; Pichora-Fuller, Schneider, & Daneman, 1994; Plomp & Mimpen, 1979b). The factors that contribute to this decline in ability are most likely related to central auditory processing deterioration than to a peripheral cochlear impairment when PTA is within normal hearing thresholds. Research examining the performance of older adults on speech-in-noise tests (Dubno et al., 1984; Pichora-Fuller et al., 1994; Plomp & Mimpen, 1979b) suggests that frequency selectivity declines and that more top-down processing effort is required to deal with the ambiguity of speech information in background noise.

Could the issue lie with working memory? Miller (1956) established the concept that short-term working memory is limited. The capacity of working memory to recall information is general set at seven pieces of information, plus or minus two. The digit triplet test simply requires that participants recall only three numbers. The speech material (digits) used is common and is one of the least mentally taxing stimuli to use in testing (McArdle & Wilson, 2009). It is expected therefore that the recall of three digits is well within the normal range for normal functioning adults (Miller, 1956; Shiffrin & Nosofsky, 1994; R. Wilson & Weakley, 2004). Research has shown that monosyllabic words have minimal effect on working memory performance and that poor listening performance by older NH participants is likely to be due to other factors (McArdle & Wilson, 2009; Miller, 1956; Shiffrin & Nosofsky, 1994; R. Wilson & Weakley, 2004). However, Pichora-Fuller et al. (1994) report that the ability of young adults to recall digits and other speech material in noise was poorer compared to their ability to recall the same material when it was presented in quiet. Pichora-Fuller et al. (1994) also found no effect of age-related working memory deficits for material that was *read* ; however, they found a significant effect on working memory for material that required *listening* (heard material). Further research found that this effect is not related to cognitive processing. The decline in the recall of items in noise was attributed to the effort needed to process misheard words by the auditory system. In other words, a decline in auditory processing abilities in older listeners can result in the allocation of more working memory resources to processing the speech material leaving less working memory resources for recalling the stimuli thus they are prone to making more errors (Patterson, Nimmon-Smith, Weber, & Milroy, 1982; Pichora-Fuller et al., 1994). This may provide some framework for understanding why one group of older adults with normal PTA thresholds failed the DTT and another group passed.

The same group of participants who had PTAs > 20 dB HL failed both the binaural and separate ear DTT tests. The analysis revealed the tests provided consistent results to this group of participants. Twenty-nine participants achieved an ‘insufficient’ or ‘poor’ rating regardless of the test condition. This showed that those participants with HI received consistent feedback from all three test conditions. One participant who achieved a normal rating for the binaural test and one separate ear test but failed the other separate ear test condition did so because they had an asymmetrical hearing impairment. A person with asymmetrical hearing loss who performs all three test conditions would find that the recommendations would vary for each test condition due to the asymmetry. The advantage of having a website version of the DTT is that further information about these types of mixed results can be provided to individuals with appropriate recommendations.

Because the binaural testing condition could classify a mild-moderate asymmetry hearing loss as ‘normal’, it may be important to consider offering only separate ear testing on the website. Further consideration should be given to whether a binaural option should be made available on the website. Comparing the NH binaural and separate ear results revealed that the various test conditions were significantly correlated to the PTA and able to reliably identify the NH from the HI when no asymmetry exists.

12.4 Relationship of Age and Sex to PTA and DTT Thresholds

The data from this study showed that male age was strongly positively correlated with the mean PTA ($r = 0.655$, $p < 0.001$) and DTT threshold ($r = 0.731$, $p < 0.001$). In contrast female age was not correlated with the mean PTA ($r = 0.268$, $p = 0.0212$) or DTT threshold ($r = 0.32$, $p = 0.00549$). These findings are not unusual and are generally representative of findings in most Western countries. Greville (2001, 2005) examined the prevalence of hearing loss in NZ and reported that males are more likely than females to have hearing loss. The higher incidence of hearing loss in males is attributable to occupational noise-induced hearing loss. Greville (2001, 2005) reports that there is a clear interaction between sex and age, noting that as people age there is a greater prevalence of presbycusis. In the USA, hearing loss is the third most prevalent condition that increases with age (Yueh et al., 2010). Research by Smith, Mitchell, Wang & Leeder (2005) shows that there are approximately 1.5 million Australians aged over 55 years with some degree of bilateral hearing loss, and that hearing loss is the second-highest ranked disability for Australian men and the eighth-highest ranked disability for Australian women. Smits et al. (2006) conducted a study involving 1,086 participants over the age of 60 years and 128 young adults between the ages of 20 - 30 years. The testing involved using the digit triplet test developed by Smits et al. (2004) and an analysis of the SRT_n showed significant effects of age ($p < 0.001$); again, more male participants had hearing loss than female participants.

12.5 QuickSIN compared to the DTT and PTA

As part of the evaluation of the DTT it was compared to an existing speech-in-noise test. The test chosen was the QuickSIN as there are no validated NZ English speech-in-noise tests currently available. The QuickSIN was created using American English speakers. The test has been used extensively in clinical practice in the United States and is a standard test for measuring a person's ability to understand speech-in-noise. The QuickSIN test quantifies a person's ability to hear in noise by measuring the signal-to-noise ratio loss (SNR loss) that cannot be reliably predicted using the standard PTA threshold measurement of 500 Hz – 4 kHz (Killion et al., 2004). One difference between the DTT and the QuickSIN is the speech stimuli. The DTT presents monosyllabic digits in noise which enhances the role of acoustic cues by reducing phonemic blurring that occurs with co-articulation (Wilson, McArdle, & Smith, 2007). The QuickSIN presents a list of six sentences with five key words per sentence in four-talker-babble which could provide contextual cues although the sentences are constructed to provide mainly syntactic cues with minimal semantic cues (Wilson et al., 2007). The digit triplet test is an adaptive speech-in-noise test while the QuickSIN uses sentences presented at pre-recorded signal-to-noise ratios that decrease in 5 dB steps from 25 dB to 0 dB. The dB SNRs used in the QuickSIN are 25,20,15,10,5, and 0 dB SNR which covers normal to severely impaired performance in noise (Killion et al., 2004).

Overall the QuickSIN and the binaural DTT results were significantly correlated ($r = 0.688$, $p < 0.001$) showing that both were effective at using noise to separate out NH participants from HI participants. This compares favourably with the research conducted by Wilson et al. (2007) which found that the QuickSIN and Words-in-Noise test (WIN), another monosyllabic word test, were both sensitive measures of SRT_n for separating out NH from HI participants.

The binaural PTA was only mildly correlated to the QuickSIN score ($r = 0.570$, $p < 0.001$). This is consistent with the results obtained by Wilson et al. (2007) who found that the QuickSIN was only mildly correlated ($r = 0.557$, $p < 0.001$) to a four frequency average PTA (1000, 2000, 3000, 4000 Hz). From research examining how an audiogram (PTA measure) relates to a person's ability to hear in noise Killion and Niquette (2000) conclude that there is no clear predictive power in using a person's PTA to predict their SRT_n or ability to hear in noise. This is also borne out by the only mild correlation between the PTA and the SRT_n found in this study.

13 Participant Questionnaire

Analysis of the questions found that overall the responses were positive for a hearing screening test. All 73 participants responded '*Yes*' to Question 1 (100%), that a hearing screening test like the DTT would be a valuable service. It was encouraging that participants also responded in the affirmative to Question 2 (90%) which asked if they would seek professional advice if the screening test indicated that they needed to have further hearing testing. In the age group 53-69^{+} years both sexes responded positively to seeking further professional advice. In response to whether a person would use the internet to take a hearing screening test all the participants (Question 5), both male and female, in age group 19-35 years responded in the affirmative '*Yes*' *(*100%). The most noticeable variation in the responses was in the female age group 53-69^{+} years who were less positive: 79% answered '*Yes'* while the remaining 21 % selected '*No/Unsure*'. The males in the same age group all answered '*Yes*' (100%).

When people were asked if they would trust a telephone version of the DTT (Question 7) the responses across all age groups and both sexes was less positive with 33% to 60% responding '*Unsure'.* Males aged 36-52 years were the least positive with 60% selecting '*Unsure*'. Further enquiry of these participants about why they selected '*Unsure'* revealed that they had concerns about the quality of telephone reception and the ability to hear the test over the phone in a manner that would not distort the test. It may be that people have experienced poor telephone conversation acoustics due to using poor quality phones and/or have a hearing loss that made the conversation more difficult. Research into the preferred method of screening for hearing loss in three European Union countries (UK, Germany and Netherlands) examined if people preferred a questionnaire, computer based process or telephone for taking a hearing screening test. The outcome of the study by Koopman et al. (2008) found for this study group a preference for questionnaires, followed by the internet and finally the telephone. People gave reasons for not wanting to use a telephone that focused on concerns around the confidentiality of the test information and fidelity of the telephone connection. Koopman et al. (2008) reported that respondents under the age of 65 years (P-value <0.001) preferred to use an internet screening test, which is not surprising given that internet use tends to be more prevalent among younger people. A possible reason for lack of acceptance of telephone and internet screening test among the older adults in the study is that the survey was sent to people who already had their hearing loss confirmed by an audiologist. Their experience biased them to accepting testing (i.e. diagnostic audiology) conducted only by a professional (Koopman et al., 2008). When asked about trusting an internet version of the hearing screening test (Question 8) the most positive response came from both sexes in the age group of 19-35 years. Again, this finding is not surprising given the level of usage and exposure to the internet in this age group. Both sexes in the two age groups 36-52 years and 53-69^{+} years generally responded positively to trusting an internet test, with '*Yes*' responses for both sexes ranging from 63% - 87% and '*Unsure*' being the next preferred response.

Upon reflection, the study questionnaire could have included two additional important questions. Firstly, people could have been asked to rate their own hearing ability before having a hearing test to examine the relationship between their own perception and the audiogram PTA and DTT result. Secondly, an additional question could have asked if people would pay a nominal fee for taking a telephone version of the test with the provision that the funds would be used to assist people with hearing impairment through a number of not-for-profit organisations.

While the results of the questionnaire are reflective of a highly motivated group of people who are willing to be part of a research project, the responses are still insightful and hopefully somewhat representative of the general public. It could be valuable to have an online questionnaire to gather information about people taking the hearing screening test. The information could provide government agencies and private hearing groups with valuable information about the state of hearing in NZ.

14 Amplitude of the Test

The stimuli and noise for the DTT are both made from the same speech material so that whether the test is transmitted via broadband or telephone the SNR will not be affected (Figure 7). Naturally, if a user plays the test at home at an intensity level that is inaudible then they will not pass the test. At home users of the DTT screening test will be able to use headphones or external speakers to listen to the test so it is important that the test is played at a normal, comfortable listening level for that person with limited environmental noise.

Hawkins and Stevens (1950) report that speech thresholds are not greatly affected by masking noise at low amplitude levels, but that as the noise levels are raised the threshold for speech intelligibility rises at approximately the same rate as the noise. The adaptive model used to present the DTT means that the listener's SNR is not dependent on the loudness level of the DTT via home sound systems but on the SNR of the speech and background noise. The listener has no control over the SNR of the test. Turning the volume up or down will simply distort the test and not change the relationship of the noise and speech (Smits et al., 2004).

15 Other Considerations

A limitation of the DTT as a screening tool, which applies to any hearing screening tool, is that it is not able to establish a site of lesion (Smits, 2006). Information will need to be provided on the internet version explaining this limitation and encouraging those participants in whom a hearing loss is detected to seek further diagnostic testing to quantify the type, degree and configuration of their loss.

People who take the internet version of the DTT screening test will be able to use headphones or external speakers to listen to the test. A pilot study should be undertaken to examine the effect of taking the test in a home environment, and to determine if the quality of the sound cards and speakers available to different individuals has any effect on the results of the test. Smits, Merkus, & Houtgast (2006) reported that there was a SNR difference of 1.1dB SNR ($p<0.001$) for participants who used speakers rather than headphones when taking the triplet test. Therefore, people should be encouraged to use headphones rather than speakers wherever possible.

For the telephone version, growth in the use of cellular phones and accompanying technical advances mean that a cell phone version of the test may be required. The European screening test found that cell phones gave significantly worse results compared to conventional phones in all age groups, so the investigators prevented cell phone users from taking the test (Smits, 2006). The authors of that study suggested that poor sound quality related to the phones themselves may have resulted in the less reliable results for cellular phones.

Finally, the question of requiring payment for the NZ DTT should be examined. The Dutch group charged (€0.35) per minute for their test; in addition, people were asked if they wanted to receive information about hearing from the Dutch Hearing Foundation (Smits, 2006). The NZ DTT provides an opportunity to raise funds for a number of NZ initiatives such as The National Foundation for the Deaf, The Southern Hearing Charitable Trust, The Pindrop Foundation, The NZ Audiological Society Hearing Aid fund, and The NZ Institute of Language, Brain, and Behaviour.

15.1 Implementation of the DTT

The implementation of the DTT has the potential to provide researchers in NZ with a wealth of information regarding hearing. It will be important that the design of the internet and telephone versions includes questions about age, sex and self-rating of hearing ability. A number of other countries have versions available (Table 1) that will provide a guide to the best practice for the telephone and internet versions. The Netherlands study found that the telephone version was better at reaching older adults compared to the internet version of the test (Smits, 2006). It will be interesting to see how New Zealanders compare on this measure.

16 Conclusion

This study developed a hearing screening test that has high specificity and high sensitivity which will eventually be made available to the NZ public via the internet and telephone. The test can be done in about 3m 30s and will provide test results and recommendations. Information on a range of hearing services and providers will be included on the website to increase public awareness about hearing health. The implementation of this screening programme is a step forward in promoting hearing health for the general adult population in NZ. It is hoped that the DTT will reduce the time people take in seeking help for hearing loss and raise awareness about protecting hearing.

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APPENDICES

APPENDIX I

Human Ethics Committee approval letter, project information sheets, and consent forms.

Ref: HEC 2010/38

23 April 2010

Sharon King
Department of Communication Disorders
UNIVERSITY OF CANTERBURY

Dear Sharon

The Human Ethics Committee advises that your research proposal ‘Development of a NZ version of the Digit Triplet Test (DTT)’ has been considered and approved.

Please note that this approval is subject to the incorporation of the amendments you have provided in your email of 10 April 2010.

Best wishes for your project.

Yours sincerely

Dr Michael Grimshaw
Chair, Human Ethics Committee

College of Science

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Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

PROJECT INFORMATION

Development of a New Zealand Version of the Digit Triplet Test (DTT)

There are currently no hearing screening tests suitable for mass screening of the adult population in New Zealand. The Digit Triplet Test (DTT) is a quick, inexpensive way for people to have their hearing acuity checked. The aim of this study is to develop a Digit Triplet Test (DTT) using New Zealand English. The DTT uses spoken numbers presented in background noise to estimate speech recognition thresholds. The DTT will be a hearing screening tool that people can use over a telephone or via the internet. The DTT will provide information to each person who completes the test about whether they should seek further professional testing of their hearing.

Part A: Characterisation of digit difficulty

The purpose of this specific phase of the study is to determine the degree of difficulty for each spoken number that will form part of the Digit Triplet Test (DTT). The spoken numbers will be presented in background noise and will be analysed to determine the average level of difficulty for each combination of digit and noise level. In order to determine the optimal combination of parameters, we need to test your performance on a range of spoken numbers in background noise.

You will be required to listen to a series of spoken numbers in background noise and to key in the digits you thought were presented.

Procedure:

The research will take place at the University of Canterbury. If you are interested in participating in the study, the following will occur:

1. You will be given a time to come to the University of Canterbury Communication Disorders Research Lab in Room 801 of the Rutherford Building (on the 8th floor).

2. You will be given instructions about what you are required to do in the study and given the opportunity to ask any questions before proceeding with the activities.

3. After signing the consent form, you will have your outer ear and eardrum visually inspected using an otoscope (a specialised ear torch) to determine ear health. *(Time required: 2-3 minutes).*

4. A quick hearing screening test will be completed to determine your eligibility for the study. This will comprise of pure-tone audiometry, which involves establishing whether your hearing sensitivity is normal at a range of different frequencies. To do this, you will be seated in a sound booth. Stimuli will be presented through headphones or insert ear phones at varying intensities. You will be asked to a press a button every time you hear a tone. *(Time required: 10 minutes).*

5. You will then listen to a series of digits presented in background noise via computer headphones, and will be required to key in each digit you hear. *(Time required: 20 minutes).*

6. After the test, we will ask you some questions about the test and hearing tests in general. *(Time required: 2-3 minutes).*

Results:

Although we are developing a hearing screening test, the results of this part of the study will not tell us anything in particular about *your* hearing ability. Instead, it will provide normative data to help us fine-tune the stimuli we use in the final version of the test.

Nonetheless, complete confidentiality will be assured of all collected data gathered in this study. To ensure confidentiality all collected data will be stored in a locked filling system within the Communication Disorders Department. Results obtained will be stored on a computer, and will be password protected. Only those individuals directly involved in this study will be able to access this data.

Withdrawal:

These tests are perfectly safe and will in no way cause you any discomfort or harm. Your participation in this study is voluntary (your choice) and you can withdraw from the study at any time, including the withdrawal of any information provided. If you should choose to withdraw your participation in this study it will in no way affect any further services or interactions you have with the University of Canterbury or the University Speech and Hearing Clinic.

Questions:

The project is being carried out as a part of a Masters of Audiology by Sharon King under the supervision of Dr Greg O'Beirne, Dr Natalie Rickard and Dr Megan McAuliffe. We will be pleased to provide any further information about the study and discuss any concerns you may have about participation in the study.

The project has been reviewed *and approved* by the University of Canterbury Human Ethics Committee. *Thank you for choosing to take part in this study. Your participation is greatly appreciated.*

College of Science

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CONSENT FORM

Development of a New Zealand Version of the Digit Triplet Test

Part A: Characterisation of digit difficulty

DECLARATION

I (the participant) have read and understood the description and requirements of the above-named study, as outlined in the attached information sheet. Any questions I have asked have been answered to my satisfaction. On this basis, I agree to participate in this study, realising that I may withdraw at any time without it affecting any further service or interactions that I may have in the future with the University of Canterbury or the University Speech and Hearing Clinic.

I understand that all information provided is strictly confidential and will not be released by the investigator unless required to do so by law.

I agree that research data gathered in this study may be published as part of a Masters of Audiology thesis. The thesis will be a public document that will be made available when submitted via the University of Canterbury Library database. I provide consent for this publication with the understanding that confidentiality will be preserved, and my name and any other identifying information will not be used.

Print Name

Signature of Participant

Date

College of Science

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PROJECT INFORMATION

Development of a New Zealand Version of the Digit Triplet Test (DTT)

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Part B: Audiological assessment and Digit Triplet Test (DTT)

The purpose of this specific phase of the study is compare a professional audiological assessment of your hearing acuity against the results obtain taking the DTT test.

You will be required to participate in an audiological assessment of your hearing thresholds and then complete the Digit Triplet Test. The Digit Triplet Test is a hearing screening test which requires you to listen to a series of spoken numbers in background noise and to key in the numbers you thought were presented

Procedure:

The research will take place at the University of Canterbury. If you are interested in participating in the study, the following will occur:

1. You will be given a time to come to the University of Canterbury Communication Disorders Research Lab in Room 801 of the Rutherford Building (on the 8th floor).

2. You will be given instructions about what you are required to do in the study and given the opportunity to ask any questions before proceeding with the activities.

3. After signing the consent form, you will have your outer ear and eardrum visually inspected using an otoscope (a specialised ear torch) to determine ear health. *(Time required: 2-3 minutes).*

4. A hearing test will be completed if you have not made available to the study a recent audiogram that has been completed by an audiologist in the last 6 months. The hearing test will comprise of pure-tone audiometry including a speech-in-noise test which involves establishing your hearing thresholds across a range of different frequencies. To do this you will be seated in a sound booth. Stimuli will be presented through headphones or insert ear phones at varying intensities. You will be asked to a press a button every time you hear a tone. For the speech test you be asked to repeat back a series of sentences. *(Time required: 20 minutes).*

5. You will then listen to a series of digits presented in background noise via computer headphones, and will be required to key in each digit you hear. *(Time required: 20 minutes).*

6. After the test, you will be asked some questions about the test and hearing tests in general. *(Time required: 2-3 minutes).*

Results:

The results of the study will provide us with information about your hearing ability. The results of the hearing test will be provided to you if you wish to have this information and any questions about these results will be answered. If you require further testing or information beyond the scope of this project you will be referred to the University of Canterbury Speech and Hearing Clinic to discuss your concerns with an Audiologist.

Complete confidentiality will be assured for all data gathered in this study. To ensure confidentiality all collected data will be stored in a locked filling system within the Communication Disorders Department. Results obtained will be stored on a computer, and will be password protected. Only those individuals directly involved in this study will be able to access this data.

Withdrawal:

These tests are perfectly safe and will in no way cause you any discomfort or harm. Your participation in this study is voluntary (your choice) and you can withdraw from the study at any time, including the withdrawal of any information provided. If you should choose to withdraw your participation in this study it will in no way affect any further services or interactions you have with the University of Canterbury or the University Speech and Hearing Clinic.

Questions:

The project is being carried out as a part of a Masters of Audiology by Sharon King under the supervision of Dr Greg O'Beirne, Dr Natalie Rickard and Dr Megan McAuliffe. We will be pleased to provide any further information about the study and discuss any concerns you may have about participation in the study.

The project has been reviewed *and approved* by the University of Canterbury Human Ethics Committee. *Thank you for choosing to take part in this study. Your participation is greatly appreciated.*

College of Science

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CONSENT FORM

Development of a New Zealand Version of the Digit Triplet Test

Part B: Audiological assessment and Digit Triplet Test

DECLARATION

I (the participant) have read and understood the description and requirements of the above-named study, as outlined in the attached information sheet. Any questions I have asked have been answered to my satisfaction. On this basis, I agree to participate in this study, realising that I may withdraw at any time without it affecting any further service or interactions that I may have in the future with the University of Canterbury or the University Speech and Hearing Clinic.

I understand that all information provided is strictly confidential and will not be released by the investigator unless required to do so by law.

I agree that research data gathered in this study may be published as part of a Masters of Audiology thesis. The thesis will be a public document that will be made available when submitted via the University of Canterbury Library database. I provide consent for this publication with the understanding that confidentiality will be preserved, and my name and any other identifying information will not be used.

Print Name:__________________

______________________________ ________________

Participant Date

University of Canterbury Private Bag 4800, Christchurch 8020, New Zealand. **www.canterbury.ac.nz**
Version 2.0, 10 April, 2010

APPENDIX II

Questionnaire

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Development of the New Zealand Digit Triplet Test

Instructions:

Today you have completed the Digit Triplet Test (DTT) which is a hearing screening test. **The following are questions about this test**. Even if you have had your hearing tested by a professional would you please think about whether you think hearing screening tests are useful.

Please circle the following:

You are:	Male		Female		
Age range:	18 – 30	31-43	44-56	57-69	over 70

1. Do you think that a hearing screening test like the Digit Triplet Test you took today would be a valuable service?

   Yes Not Sure No

2. If the Digit Triplet screening test told you that you might have a hearing loss, would you seek a more detailed hearing test from a professional to find out more?

   Yes Not Sure No

3. Would you use a hearing screening test such as the Digit Triplet Test if it was available over the telephone? (The test would provide you with results and a brief explanation and recommendation).

   Yes No

4. Do you have internet service at home?

   Yes No

5. Would you use a hearing screening test such as the Digit Triplet Test if it was available on the internet? (The test would provide you with results and a brief explanation and recommendation).

   Yes Not Sure No

If you answered "Yes" to this question please answer the following two questions before moving on to question 6. If answered "Not Sure" *or* "No" *please go directly to question 6.*

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Version 2.1, 25 September, 2010

i. Does your home computer have external speakers that you could use to listen to a hearing screening test available on the internet?

Yes Not Sure No

ii. Do you have headphones that you could use with the computer to listen to a hearing screening test available on the internet?

Yes Not Sure No

6. Do you trust that the result of the Digit Triplet hearing screening test you have taken today is accurate?

Yes Not Sure No

7. Would you trust a **telephone** Digit Triplet hearing screening test which provided you with results and an explanation?

Yes Not Sure No

8. Would you trust **an internet** Digit Triplet hearing screening test that provided results and an explanation?

Yes Not Sure No

9. Would you recommend a hearing screening like the Digit Triplet Test to other people?

Yes Not Sure No

10. Which ear do you use to listen to people when talking on the telephone? *(please circle one answer)*

Right Ear Left Ear